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Rocketdyne, Canoga Park, Calif

Prepared for

Robert A Taft Water Research Center, Cincinnati, Ohio Advanced Waste Treatment Research Lab

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THE U-TUBE FOR WATER AERATION

Final Report

Rocketdyne
A Division of North American Rockwell Corporation
Canoga Park, California

March 1970

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THE U-TUBE FOR WATER AERATION

by

R. C. Mitchell and A. D. Lev

for

The Advanced Waste Treatment Research Laboratory

Robert A. Taft Water Research Center

This report is submitted in
fulfillment of Contract No. 14-12-434
between the Federal Water Pollution
Control Administration and Rocketdyne,
A Division of North American Rockwell
Corporation, Canoga Park, California

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Cincinnati, Ohio

March 1970

FOREWORD

In its assigned function as the Nation's principal natural resource agency, the United States Department of the Interior bears a special obligation to ensure that our expendable resources are conserved, that renewable resources are managed to produce optimum yields, and that all resources contribute their full measure to the progress, prosperity, and security of America -- now and in the future.

This series of reports has been established to present the results of intramural and contract research studies carried out under the guidance of the technical staff of the FWPCA Robert A. Taft Water Research Center for the purpose of developing new or improved wastewater treatment methods. Included is work conducted under cooperative and contractual agreements with Federal, state, and local agencies, research institutions, and industrial organizations. The reports are published essentially as submitted by the investigators. The ideas and conclusions presented are, therefore, those of the investigators and not necessarily those of the FWPCA.

Reports in this series will be distributed as supplies permit. Requests should be sent to the Office of Information, Ohio Basin Region, Federal Water Pollution Control Administration, 4676 Columbia Parkway, Cincinnati, Ohio 45226.

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This is the final report submitted under Rocketdyne G.O. 09108 in compliance with Contract No. 14-12-434 with the Federal Water Pollution Control Administration, Department of the Interior. The research reported herein was performed during the period of 29 June 1968 through 29 September 1969. This project was sponsored by the Cincinnati Water Research Laboratory of the FWPCA, with Mr. C. L. Swanson acting as the Project Officer.

This program was conducted by the Environmental Technology organization of the Rocketdyne Research Division, with Dr. B. L. Tuffly serving as Program Manager and Dr. R. C. Mitchell serving as Responsible Engineer. The following technical personnel also contributed to the work described in this report: A. D. Lev, B. Minnich, J. D. Perret, F. D. Raniere, R. Rushworth, and K. J. Youel.

This report has been assigned Rocketdyne identification number R-8043.

ABSTRACT

The results of a 15-month experimental and analytical project to investigate and begin development of the U-tube aeration concept are presented. Three major tasks were accomplished: (1) experimental verification of oxygen transfer efficiencies and exploration of practical aspects of U-tube operation; (2) analytical investigation of two major applications--post-aeration of effluent from a sewage treatment plant and in-situ aeration of sanitary sewer flows to prevent anaerobic conditions; (3) investigation and design of prototype U-tube systems, with particular emphasis on designs for installation in the Jefferson Parish, Louisiana sewer system. It was found that the U-tube is a practical, efficient method for aerating a moving water or waste water stream.

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INTRODUCTION AND SUMMARY

There are many requirements for aerating water and a variety of techniques which can be used to meet these requirements. One interesting and little-known aeration method is the U-tube concept. This type of aeration system is simple in concept, basically consisting of two elements: (1) a device for entraining air (or oxygen) into a flowing water stream (e.g., an aspirator device or a compressor introducing air through a diffuser), followed by (2) a vertical U-shaped flow path to provide residence time in a zone of above-atmospheric pressure during which oxygen absorption from the entrained air can take place. The U-shaped flow path can take various forms, e.g., a pair of vertical pipes connected by a 180-degree return bend at the bottom, or a pair of concentric pipes with flow downward through one passage and upward through the other.

The label "U-tube" was apparently first used in the literature by Bruijn and Tuinzaad,[1] although the original aeration experiment they describe (using an aspirated-air U-tube) was conducted by the Dutch Research Institute K.I.W.A. Related aeration systems were considered perhaps 40 years ago;[2] however, there appear to have been no other investigations of the U-tube concept, per se, until very recently. Rocketdyne has been studying and developing this aeration technique in various forms, first under internal funding[3] and later under FWPCA sponsorship as described in this report. New Mexico State University has been studying the U-tube with compressed air injection.[4]

A 15-month experimental and analytical effort, initiated in June 1968 under FWPCA Contract No. 14-12-434, was conducted by Rocketdyne to investigate and begin development of the U-tube aeration concept for various wastewater applications. Three major tasks were accomplished: (1) experimental verification of oxygen transfer efficiencies and exploration of practical aspects of U-tube operation; (2) analytical investigation of two major applications--post-aeration of effluent from a sewage treatment plant, and in-situ aeration of sanitary sewer flows to prevent anaerobic conditions; (3) investigation and design of prototype U-tube systems, with particular emphasis on designs for installation in the Jefferson Parish, Louisiana sewer system.

The complete results of this project are described in this report. Experimental data are presented to characterize the mass transfer and fluid dynamics behavior of a representative prototype U-tube system over large ranges of design variables and operating conditions. An analytical model of a U-tube aeration system is described and then applied, using experimental data, to make predictions of performance and operating characteristics of large-scale U-tube systems in various applications.

Particular detail is given for an actual application in which four U-tube systems were designed for installation in Jefferson Parish, Louisiana under FWPCA Grant 11010 ELP for in-line aeration of sewers to prevent the onset of septic conditions.

It was found that the U-tube technique is a practical, flexible, efficient method for aeration. It is particularly well-suited to applications for raising the dissolved oxygen concentration of a moving stream, perhaps even to near-saturation. There is ample flexibility in the choice of U-tube configurations plus other design variables to permit efficient specific designs in a wide variety of applications and requirements. U-tube aeration systems require little space, can be designed with no moving parts, require no operating labor and little maintenance, and have substantial cost savings over "conventional" aeration methods. It is strongly recommended that U-tube aerators be considered in any application which requires raising the dissolved oxygen level of a flowing water or wastewater stream.

EXPERIMENTAL STUDIES

OXYGEN TRANSFER

Basic experiments with deoxygenated tap water were conducted in a pilot scale (2-inch diameter) U-tube aerator. Four hundred ten (410) test runs were made over a 4-month period. Data relevant to oxygen transfer and pressure loss were obtained as functions of U-tube depth, water velocity, air-to-water ratio, and air aspirator configuration. Five U-tube depths were investigated, ranging from 9 to 45 feet. Head loss through the system varied from 1 to 8 feet. Superficial water velocity (i.e., velocity of water if no air were present) varied from 1.4 to 3.4 ft/sec with a few runs above and below this range. The air-to-water volume ratio was varied from zero to approximately 0.2. Two air aspirator designs were investigated. Runs 1 through 94 were made with a tapered center-plug aspirator configuration. When it became apparent that permanent pressure losses across this device were excessive, a second aspirator was constructed; runs 95 through 410 were made with this venturi aspirator. Performance in terms of pressure loss was markedly better for the venturi design.

Apparatus

The pilot scale U-tube aerator was located in the Igniter Development Area (IDA) of Rocketdyne's Santa Susana Field Laboratory. The tube was suspended from the 30-foot platform of an existing steel tower, with associated tanks and instrumentation mounted on the platform. A schematic diagram of the experimental system is shown in Fig. 1.

The U-tube was constructed of 2-inch diameter pipe and hose. The downleg contained a ten-foot section of glass pipe located just below the aspirator exit. The remainder of the U-tube consisted of 8 to 10-foot sections of 12-inch PVC pipe joined with threaded unions. This segmented construction made it easy to change depth. A section of 2-inch steel-reinforced rubber hose was installed in the top portion of the up-leg to make it possible to vary the head loss across the system by moving the adjustable height bracket. The auxiliary plumbing shown in Fig. 1 was fabricated primarily of stainless steel tubing. The return bend initially used was a 2-inch diameter glass section (made by Kimble Glass Co.) with pipe thread end adaptors. During the program a changeover was made to a return bend of two 90-degree elbows and a short pipe nipple. This change was due to difficulty in aligning the legs of the U-tube at the shorter lengths with the glass return bend.

The deaeration, surge, and U-tube tanks had approximate capacities of 100, 50, and 31 gallons, respectively. The deaerator feed pump was a 1/2-hp centrifugal pump rated for approximately 50 gpm at 40 feet of

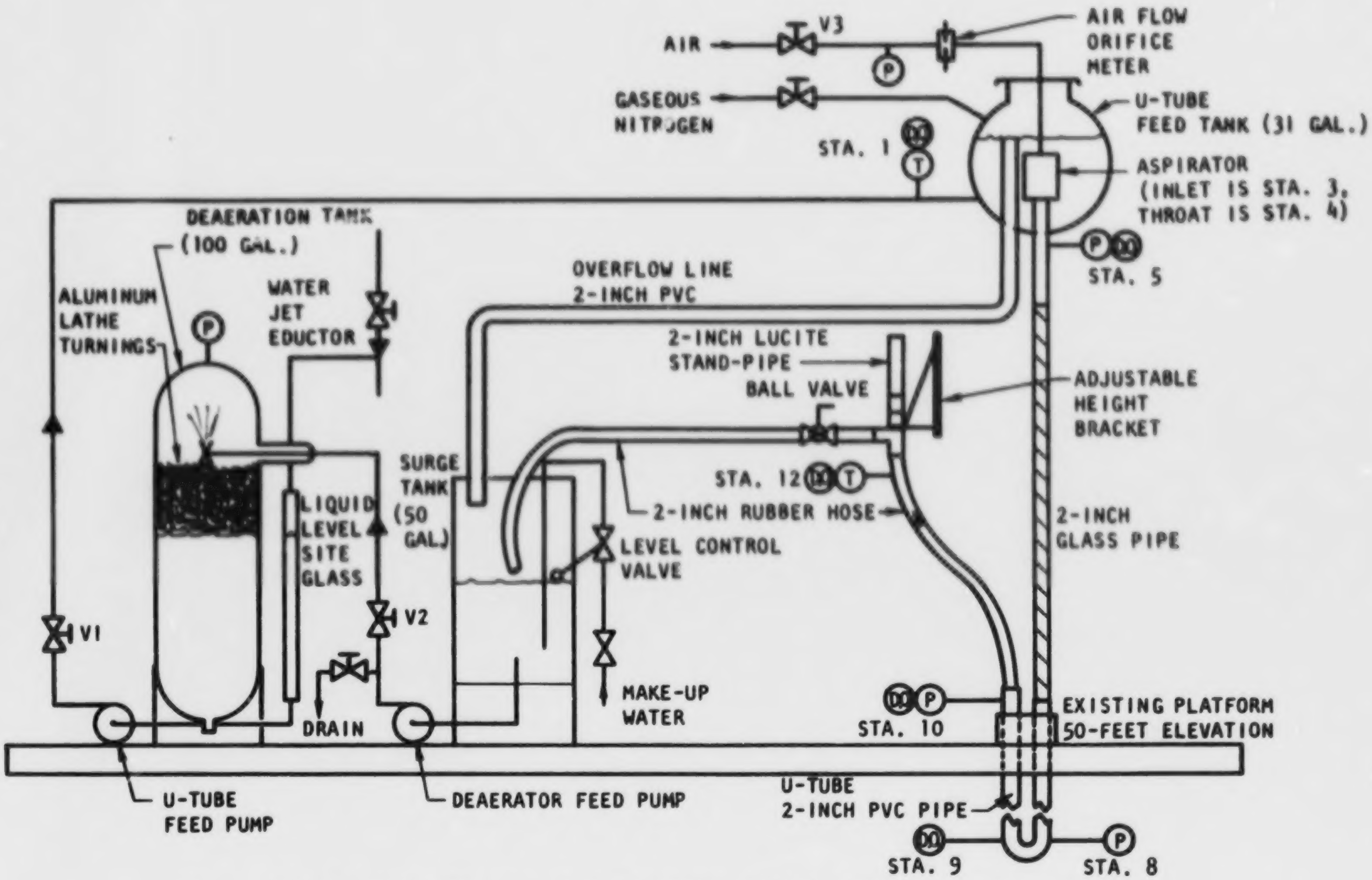

AIR
V3
AIR FLOW ORIFICE METER
GASEOUS NITROGEN
P
U-TUBE FEED TANK (31 GAL.)
STA. 1
T
ASPIRATOR (INLET IS STA. 3, THROAT IS STA. 4)
DEAERATION TANK (100 GAL.)
P
STA. 5
ALUMINUM LATHE TURNINGS
WATER JET EDUCTOR
OVERFLOW LINE 2-INCH PVC
2-INCH LUCITE STAND-PIPE
BALL VALVE
ADJUSTABLE HEIGHT BRACKET
SURGE TANK (50 GAL.)
STA. 12
2-INCH RUBBER HOSE
LIQUID LEVEL SITE GLASS
LEVEL CONTROL VALVE
2-INCH GLASS PIPE
V1
V2
MAKE-UP WATER
DRAIN
STA. 10
EXISTING PLATFORM 50-FEET ELEVATION
U-TUBE FEED PUMP
DEAERATOR FEED PUMP
U-TUBE 2-INCH PVC PIPE
STA. 9
STA. 8

Figure 1. Schematic Diagram of U-Tube Experimental Apparatus

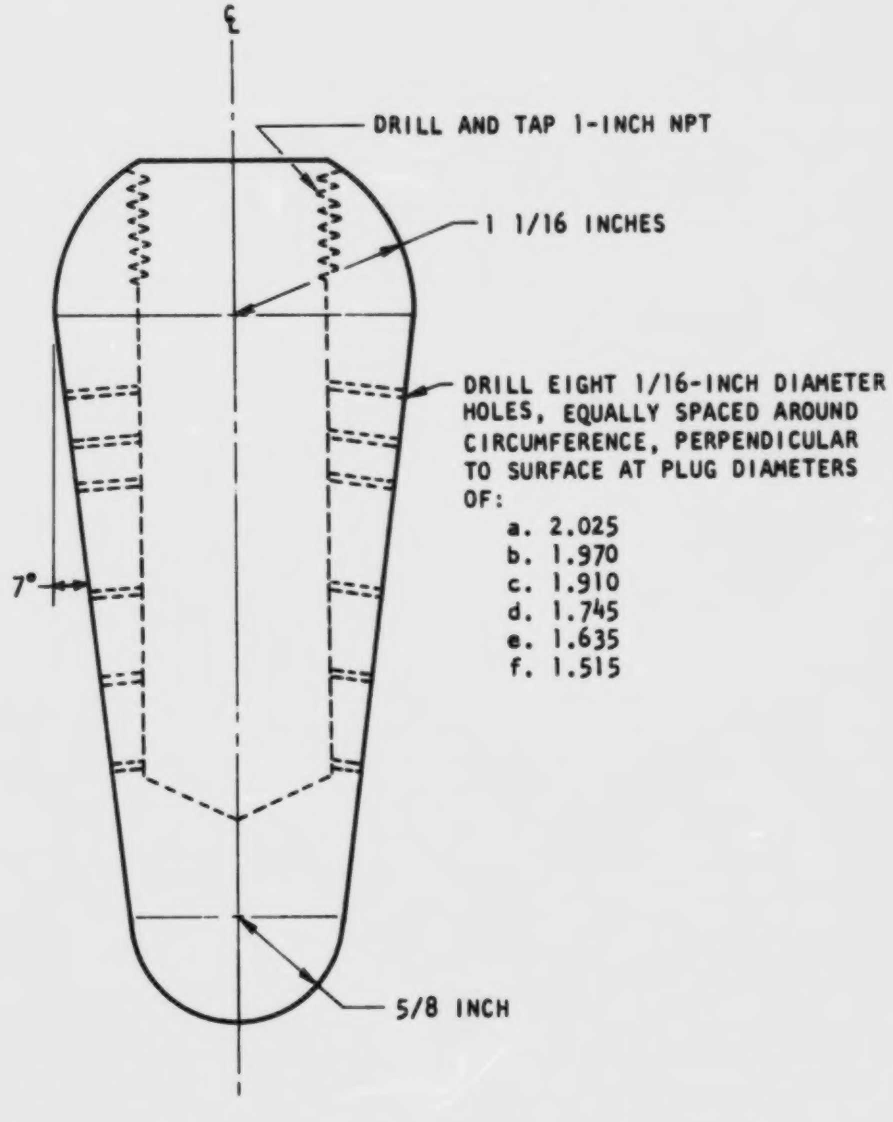
discharge head. The U-tube feed pump was a 5-hp centrifugal pump rated for 160 gpm at 70 feet of head. Gate valves were used for water flow control.

The center-plug aspirator consisted of a hollow, tapered aluminum plug which was set in a cone attached to the entrance of the U-tube (Fig. 2). Six sets of radial holes were placed at different diameters in the plug, and all or part of the holes could be used as desired. The constricted annular flow area at the U-tube entrance (between the plug and the 2.067-inch inside diameter of the pipe) caused accelerated water velocity and reduced pressure, resulting in aspiration of air through the plug holes into the water stream. A pipe attached to the core o the plug was connected to the air flow orifice meter. By raising and lowering the plug, variable annular areas (contraction ratios) were attained. Initially, the plug was used without a flow collimating cone. The cone was added when it became apparent that for efficient aspiration, the water flow had to be aligned somewhat parallel to the plug surface.

The second aspirator used was basically a Herschel-type venturi with inlet and exit full-cone angles of 21 and 7 degrees, respectively. Figure 3 is the venturi construction drawing. The unit was machined from 6061 aluminum. The venturi had a contraction area ratio of 8 based on the full flow area of 2-inch PVC pipe (2.067-inch I.D.). Entrance pressure loss was minimized by designing for low entering water velocity (i.e., providing a large diameter entrance). A threaded section on the diffuser cone enabled the unit to be screwed into the bottom of the feed tank. Air was manifolded into 4 ports at the throat (Fig. 4). A pipe attached to the manifold was connected to the air flow orifice meter. A lucite orifice meter was constructed and calibrated for measuring air flow. The differential pressure across the orifice was measured with an inclined water manometer.

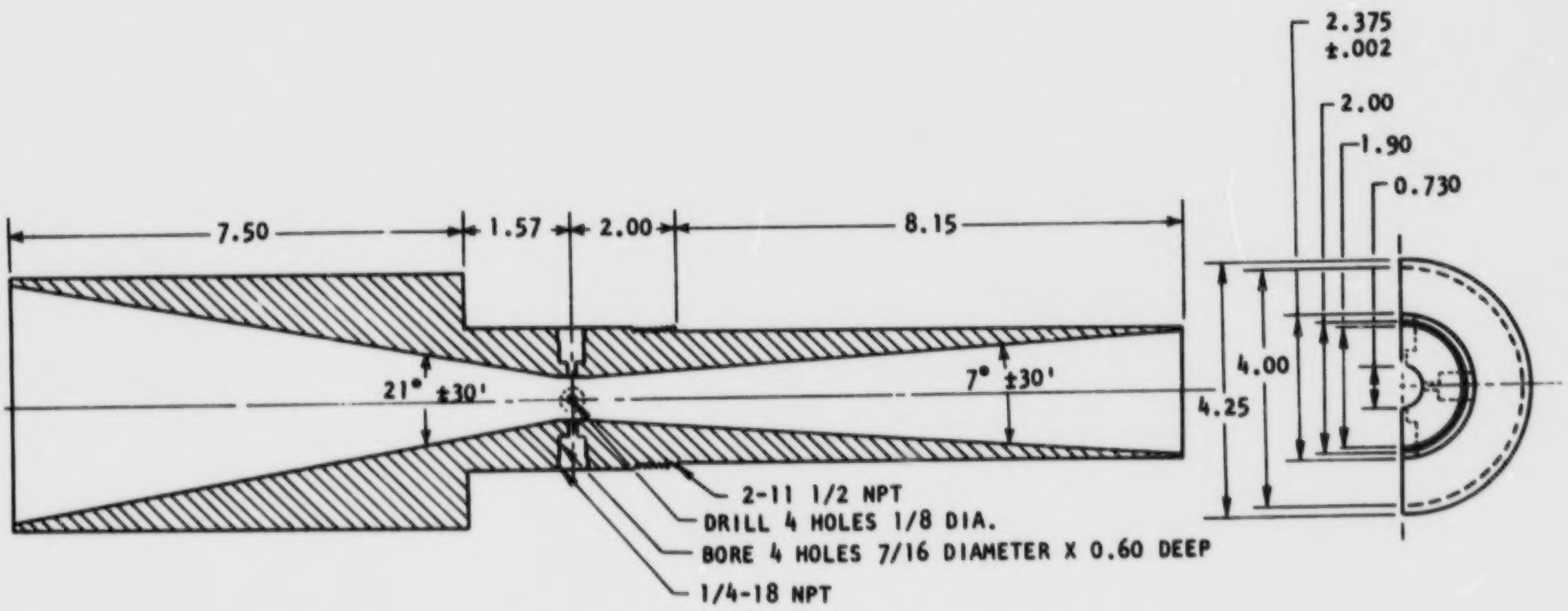
Three Beckman Dissolved Oxygen Analyzers were used for monitoring dissolved oxygen — two Model 778 process analyzers and one Model 777 laboratory analyzer. Two permanent probes were placed at Stations 1 and 12 (see Fig. 1) for monitoring inlet and outlet dissolved oxygen. The third probe was used for making intermediate D.O. measurements at Stations 5, 9, or 10 (as shown in Fig. 1).

Intermediate pressure loss measurements were made at three stations: 5, 8, and 10. Pressures at these stations were measured by use of water manometers constructed of 1/4-inch tubing, with the top 5 to 7 feet made of Tygon (clear plastic tubing) so that the liquid level could be observed. Pressure fluctuation dampers and air bubble traps were installed at the fittings. The differential height between the feed tank liquid level and the level in the water columns represented the pressure loss to the various stations. The lucite standpipe, ball valve, thermometer and dissolved oxygen probe, shown at the exit of the U-tube in Fig. 1, were attached to the adjustable height bracket.



℄
DRILL AND TAP 1-INCH NPT
1 1/16 INCHES
DRILL EIGHT 1/16-INCH DIAMETER HOLES, EQUALLY SPACED AROUND CIRCUMFERENCE, PERPENDICULAR TO SURFACE AT PLUG DIAMETERS OF:
a. 2.025
b. 1.970
c. 1.910
d. 1.745
e. 1.635
f. 1.515
7°
5/8 INCH

Figure 2. Plug Design for Center-Plug Aspirator


2.375
±.002
2.00
1.90
0.730
7.50
1.57
2.00
8.15
21° ±30'
7° ±30'
4.00
4.25
2-11 1/2 NPT
DRILL 4 HOLES 1/8 DIA.
BORE 4 HOLES 7/16 DIAMETER X 0.60 DEEP
1/4-18 NPT

NOTE:

1 ALL DIMENSIONS ARE ±.01 IN. UNLESS OTHERWISE SPECIFIED
2 THROAT TO BE 0.50 LONG
3 2-INCH PIPE THREADS TO BE 1 1/4 LONG
4 1/4-INCH PIPE THREADS TO BE 3/8 DEEP

Figure 3. Venturi Aspirator Design

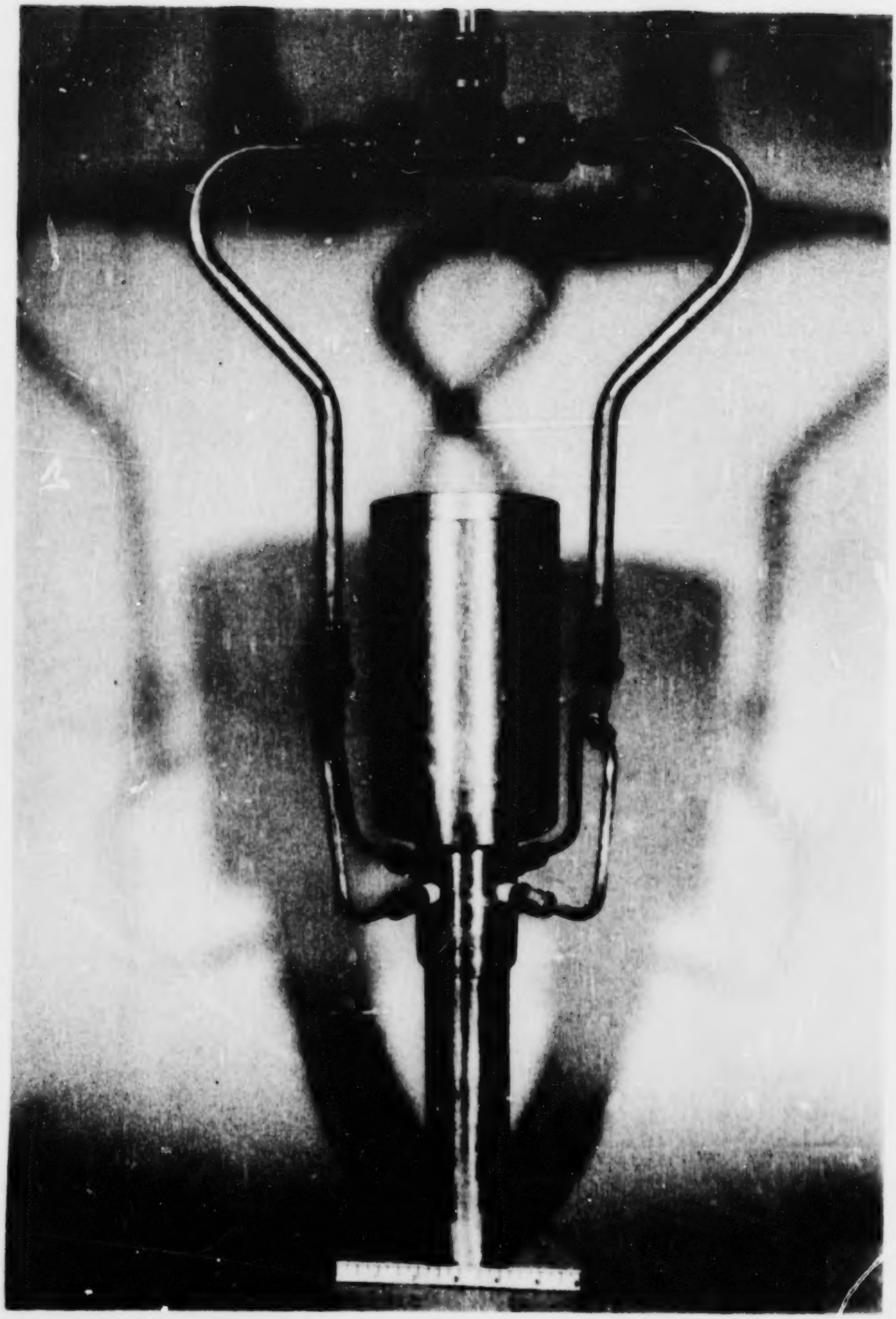


Figure 4. Venturi Aspirator Assembly with Inlet Air Manifold (Scale is in inches)

A laboratory investigation was conducted to develop techniques for measuring dissolved oxygen concentration in the water (which also contains entrained air) flowing through the U-tube experimental system. It was judged that rapid in-line measurements would be more efficient from experimental operating considerations and would avoid the difficulties with sampling and de-entrainment of the undissolved gases for a sampling-chemical analysis method. After various laboratory trials, it was found that very satisfactory D.O. measurements could be made in a two-phase air-water flowing stream with a Beckman polarographic probe if the probe axis was oriented approximately 30 to 60 degrees downstream from a position perpendicular to the pipe's centerline axis. With such an orientation, the problems with impingement and attachment of air bubbles are eliminated. It was also found, with the probes and instruments used in this study, that a stream velocity as low as 1.0 ft/sec was sufficient to ensure accurate, stable D.O. readings which were independent of flow velocity (the manufacturer's literature recommends a more conservative value of 1.8 ft/sec). The assemblies for installing the D.O. probes into the experimental U-tube system piping consisted of a standard Beckman sealed gland assembly which was slightly modified and welded into a 4-inch long pipe nipple at a 45-degree angle. This nipple adapted to 2-inch PVC pipe fittings, thus functioning as a 45-degree tee. The D.O. probe was installed in the sealed gland assembly in such a way that the probe axis was oriented approximately 45-degrees downstream from a position perpendicular to the pipe center line, and with the probe face extending about 1/2-inch from the pipe wall into the flowing stream.

Facility Operation

Operation of the system was as follows: Make-up tap water was introduced into the surge tank through the liquid level control valve. Water was pumped into the deaeration tank where dissolved gases were removed under vacuum. The deaerator was evacuated to a vacuum greater than 25 inches Hg by a Penberthy water jet eductor, which was connected to the ullage space above the packed bed. Water entered the deaerator through solid cone spray nozzles and was allowed to trickle over a bed of aluminum lathe turnings in the tank ullage. The deaerated water was then pumped up to the U-tube feed tank where a fraction of the water overflowed to the surge tank while the bulk of the flow entered the U-tube. The overflow allowed control of a constant liquid head above the aspirator, which could be varied by changing the length of the overflow pipe in the feed tank. Water leaving the U-tube entered a tee attached to the adjustable height bracket (Fig. 1). A 2-inch diameter lucite standpipe screwed into the run of the tee acted as a vacuum break for the system. The water then returned to the surge tank. The vertical distance between the water level in the feed tank and the water level in the lucite standpipe established the head loss (ΔH) across the system.

Once the tanks were brought to their operating levels and the U-tube was full, all water was recycled. Water in the surge and deaeration tanks was held at each desired steady-state level by throttling the pump discharge valves (V1 and V2 in Fig. 1).

Experimental Procedures

A typical test run commenced by setting the approximate desired ΔH across the U-tube. System ΔH was set by varying the level of the adjustable height bracket at Station 12. The dissolved oxygen probes were then calibrated in air to 100 percent saturation and placed in their adaptor gland assemblies. With the tapered plug aspirator, a precontraction ratio was selected and then set by backing the plug a predetermined vertical distance away from its seated position (seating the plug closed the U-tube entrance). No adjustment was necessary with the venturi aspirator. With the air inlet valve (V3) closed, the pumps were started. Liquid levels in the deaeration and surge tanks were set, and the water jet eductor was turned on. The system was allowed to run until the deaerator reached a steady-state pressure and the inlet and outlet dissolved oxygen meters gave identical readings.

After attaining steady-state operation with only water flowing, the air inlet valve was opened. At a given air flowrate, water flowrate measurements were made by diverting the return to the surge tank into a 5-gallon container and measuring the time to fill with a stopwatch. Four measurements were made for each run to ensure steady-state operation and a reliable average flowrate. Initially, an orifice flowmeter was placed in the return line to the surge tank for determination of water flow. The orifice gave oscillating differential pressure readings, added to the system ΔH (causing overflow in the lucite standpipe at certain (ΔH settings), and hindered the flexibility of the ΔH setting. The orifice plate was removed in favor of a bucket and stopwatch measurement technique before the start of experimentation. For Runs 1 through 25, water flowrate was allowed to vary randomly at a given air setting. After Run 25 the air flow, the plug setting, and/or the system ΔH were generally set so that the water flowrate obtained was 15, 20, 25, 30 or 35 gpm plus or minus 1 gpm. After steady-state conditions were obtained, dissolved oxygen measurements, pressure losses, ΔH setting, plug aspirator setting, air and water flowrates, and water temperature were recorded.

The next run was made by either adjusting the air throttle valve, adjusting the plug setting, and/or resetting the ΔH across the system (all while the pumps were running), and then following the same data acquisition procedures. In this way a series of water flowrate vs air-to-water ratio measurements was made as a function of system ΔH or plug setting for each U-tube length. At each new U-tube length a series of single-phase (no air) runs was made to characterize the system pressure drop in terms of water flow only.

System Operating Behavior

The performance of the U-tube is directly related to the phenomenon of vertical, gas-liquid two-phase flow. Such effects as start-up instability, oscillating flows, regime shifts, up-leg pressure recovery, and trade-off of air-water flowrate vs pressure loss were important to the experimentation. Because the explanation of these effects is based on two-phase flow phenomena, a short, qualitative description of the field is in order.

Two-phase vertical flow is characterized by a series of regimes or patterns which are dependent on air-to-water ratio, water flowrate, and pipe diameter. A visual summary of these regimes is sketched in Fig. 5, taken from a review paper by Anderson and Russell[5]. Steady-state U-tube operation is represented by the bubble flow regime, a continuous liquid phase with the gas homogeneously dispersed as bubbles. Anomalous flow behavior was usually due to approaching slug flow or the actual onset of slug flow. Froth, annular, and mist flow were not encountered in this investigation. The slug flow regime is visually characterized by consecutive passage of alternate slugs of liquid and bullet-shaped slugs of gas. In contrast to the other regimes, it is also characterized by varying pressure drops, i.e., pressure fluctuations at a fixed station in the system.[6]

The dependence of flow regime on air-to-water ratio is visually apparent from Fig. 5. The dependence on pipe diameter is more subtle. Although a precise quantitative equation for predicting the diameter functionality of the regimes is not available, a theoretical qualitative description can be made. For the slug flow regime it is apparent that the bullet-shaped slug takes on the approximate diameter of the pipe. Given the injection of 1/4-inch diameter bubbles into 1/2-inch diameter pipe, a slight degree of bubble coalescence could cause the formation of a bubble which has the cross-sectional area of the pipe. If this occurs, slug flow would result. Furthermore, a 1/2-inch diameter slug of gas is relatively stable hydrodynamically, i.e., the slug would tend to remain in the system. In the case of 1/2-inch diameter bubbles injected into a 2-foot diameter pipe, it is apparent that a great deal of coalescence would have to occur before a 2-foot diameter slug could form. Also, a 2-foot diameter slug of gas is much less stable hydrodynamically and, therefore, would probably break up.

The shear forces at the bubble-liquid interface are proportional to water flowrate. Higher bubble-liquid interfacial shear would imply greater interfacial turbulence and lead to bubble breakup. The implication is that higher water flowrates reduce the tendency toward slug flow at a given air-to-water ratio and pipe diameter. This trend is qualitatively substantiated by the observations of Griffith and Wallis.[5]

When starting the experimental U-tube, the ΔH across the system was set before the pumps were turned on. The initial down-leg liquid level was

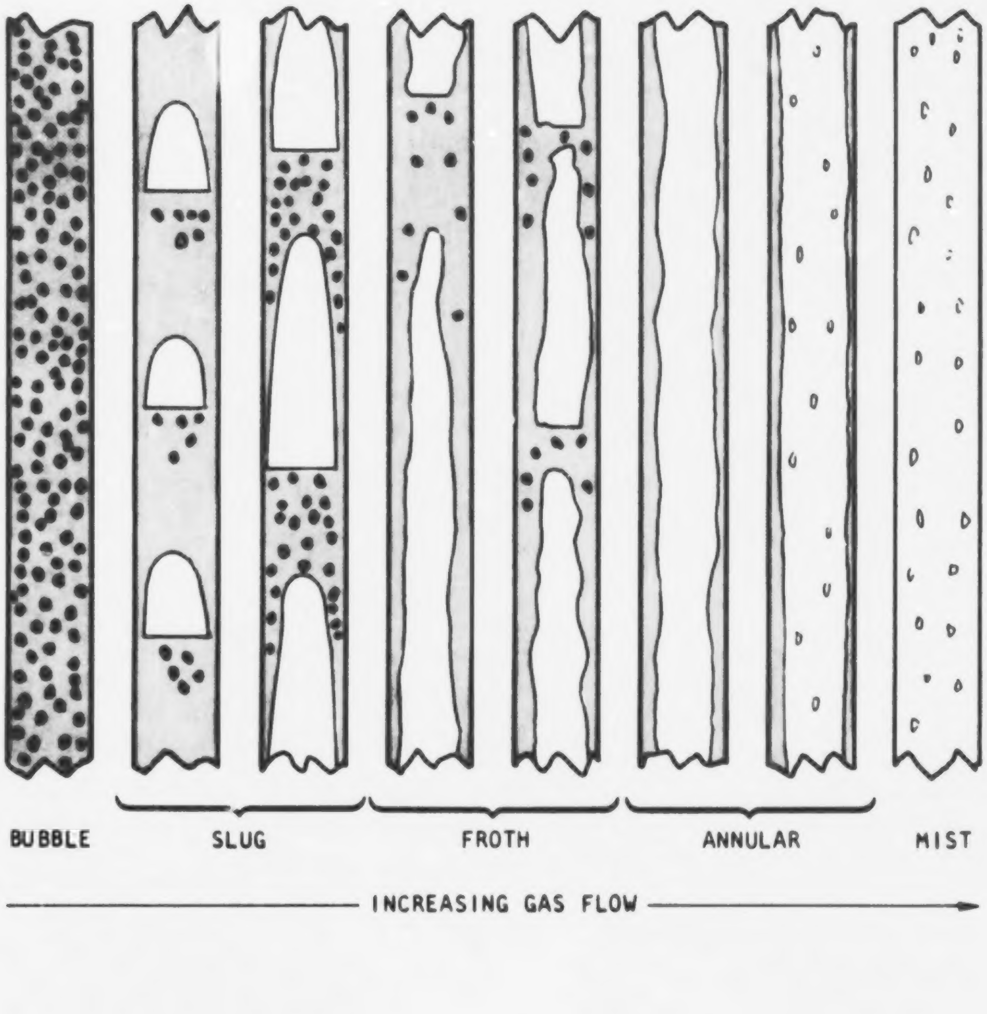

BUBBLE
SLUG
FROTH
ANNULAR
MIST
INCREASING GAS FLOW

Figure 5. Vertical Two-Phase Flow Patterns

usually in the glass pipe, leaving several feet of air between the aspirator and the liquid surface. Upon start-up, this air was flushed out of the system in the form of long air cones (slug flow). Since no additional air was allowed into the system, the pressure loss across the cones was overcome by the system ΔH, and the U-tube was rapidly flushed of air. After measurement of the single-phase water flow, air was allowed to enter the system. To hold the same single-phase water flowrate after air introduction, the system ΔH had to be increased. With the addition of more air, the ΔH had to be increased further. This is reasonable with respect to the bubble flow regime depicted in Fig. 5. Although pressure loss was incurred in the down-leg, at high air-to-water ratios and/or low water flow rates, some net pressure recovery was observed in the up-leg. This is due to the air-lift effect counterbalancing the frictional losses.

During normal bubble flow operation, very slight air flow and pressure loss oscillations were observed (with both aspirators). These oscillations did not impede data acquisition and were probably a result of the system design. At high air-to-water ratio, the oscillations increased to a noticeable level (perhaps 5 to 10 percent of the manometer reading). Observations showed the system to be still in the bubble flow regime, but with a time-dependent bubble density. In these cases, data acquisition was made by visual time averaging of pressure losses and air flows. Intermediate and outlet dissolved oxygen measurements generally showed only small oscillations (perhaps 2 percent of the reading) which were readily averaged). Of course, the water flow measurement was averaged by the nature of the technique.

Increasing the air-to-water ratio to even higher levels resulted in a transition to true slug flow. At first, small air caps would form in the dense bubble zones. With additional air, these caps coalesced into bullet-shaped cones. Very large oscillations in pressure loss, air flow, dissolved oxygen, and water flow were apparent at this time. Data flow pressure loss would eventually overcome the system ΔH. The result was upward or reverse flow in the down-leg, due to the air-lift effect of the cones. Slug flow was easily avoided in actual operation. At the largest system ΔH (approximately 8 feet), the maximum air-to-water ratio at a given water flowrate was usually in the bubble flow regime. Slug flow was encountered only at extreme conditions and usually with long U-tubes where the time for slug coalescence was great.

AIR BUBBLE CHARACTERIZATION

High-speed motion pictures of the bubbles were taken in the glass section at the top of the down-leg and at the glass return bend for the 45-foot U-tube. The 45-foot depth was selected because this was the only length permitting convenient access to the return bend. For evaluating mass transfer coefficients, information was needed regarding bubble size, shape, and slip velocity distributions, plus the change in these with respect to depth, water flowrate, and air-to-water ratio.

Pictures were taken with two Milliken high-speed cameras at approximately 400 frames per second. The cameras were set up electrically in series at the top and bottom of the U-tube enabling simultaneous photography at the two stations. Segments of nine runs were photographed for each aspirator design. Runs were selected with six different water velocities over a range of air-to-water ratios for the center-plug aspirator. Three water velocities, but a larger range of air-to-water ratios were represented in the venturi aspirator system photographs. Data were taken from enlarged projections of the pictures. The bubbles measured were close to the center line of the glass pipe to minimize distortion of the bubble dimensions. Bubble dimensions were determined for each run at each station from a random sample of bubbles. Bubble velocities were readily determined from the film speed and the number of frames required for a bubble to transverse a section of the pipe between two marks. A summary of the results will be presented in the Experimental Results section.

NITROGEN TRANSFER

Water samples were taken for two runs at inlet and outlet stations to determine the rate of nitrogen transfer relative to that of oxygen. This information was necessary for mass transfer coefficient evaluation. Quantitative analysis for dissolved gases was performed by a combination of vacuum degassing and mass spectrometry.

Water samples were taken from the inlet line to the U-tube feed tank and from the tee at the U-tube exit. Because the analytical technique could not differentiate between dissolved and entrained gases, considerable care was taken to try to eliminate air bubbles from the sample. The samplers were thoroughly cleaned, evacuated, and then pressurized with helium before sampling. Since no entrained gases were present in the inlet water, the sampling technique was straightforward. The sampler was attached to the feed tank line (after water purging the connecting line). The two valves between the line and sampler were then opened allowing the water to compress the helium to the pump discharge pressure. The upper valve on the sampler was then opened, allowing the helium to escape and water to flow. When approximately one liter had been flushed through the sampler, the sample was taken.

The outlet water sample required revised equipment and procedure because of entrained gases. A long de-entrainment column was placed between the sampler and sample station to remove entrained air from the water to be sampled. Water flowed by gravity into the middle of the de-entrainment column until the column was overflowing; water was then withdrawn for sampling from the bottom of the column. The helium pressurized sampler was reduced to atmospheric pressure and then attached to the sample system after purging of the connecting lines with water from the column. The sampler was then allowed to fill (by gravity flow) until approximately one liter had been flushed. The sample was then taken. While the sampler was filling, the column was still overflowing.

Clear tubing connecting the column to the sampler enabled observation of any entrained gases entering the sampler. The tall narrow column negated any appreciable effects of surface aeration.

Subsequently, in the analytical laboratory, dissolved oxygen and nitrogen were removed from the sample by vacuum degassing. The total quantity of gas was determined from the ideal gas law in a system of known volume. A gas sample was then analyzed on a mass spectrometer to obtain the quantitative nitrogen-oxygen ratio. The results of these analyses for the four samples will be presented in the Experimental Results section.

SILTING STUDIES

Experimental studies of silting/scouring were conducted using a concentric pipe return bend. The objective of the effort was to determine the minimum velocity necessary to begin scouring and transporting particles out of the bottom of the return bend and up the U-tube upleg. Four particle size ranges were used: U.S. Sieve No. 30-35 (0.50-0.60 mm) glass beads, U.S. Sieve No. 14-18 (1.00-1.41 mm) ground glass particles, U.S. Sieve No. 8-10 (2.00-2.38 mm) gravel, and U.S. Sieve No. 3.5-5 (4.00-5.66 mm) glass beads.

The glass U-bend on the 45-foot U-tube was removed and replaced with a concentric return configuration, shown in Fig. 6. Water flow came down the center pipe and went out the side arm. Since the study was concerned with water-solid interaction, no air was introduced through the venturi. A series of runs was made without solids to calibrate the water flow vs head loss characteristics of the system. Then, five scouring runs were made - two with the 3.5-5 mesh beads and one each with the other particle sizes.

A typical test run commenced by loading the return bend (through the venturi aspirator) with solids to some level, usually below the downleg terminus. A small ΔH was set across the U-tube and flow was started. The action and depth of scour of the solids was recorded as the system ΔH and water flow rate were increased. Water flow rate measurements were made as a check on the calibration runs. A screen was placed in the surge tank to catch solids that were flushed out of the return. The results of these tests are presented in the next section.

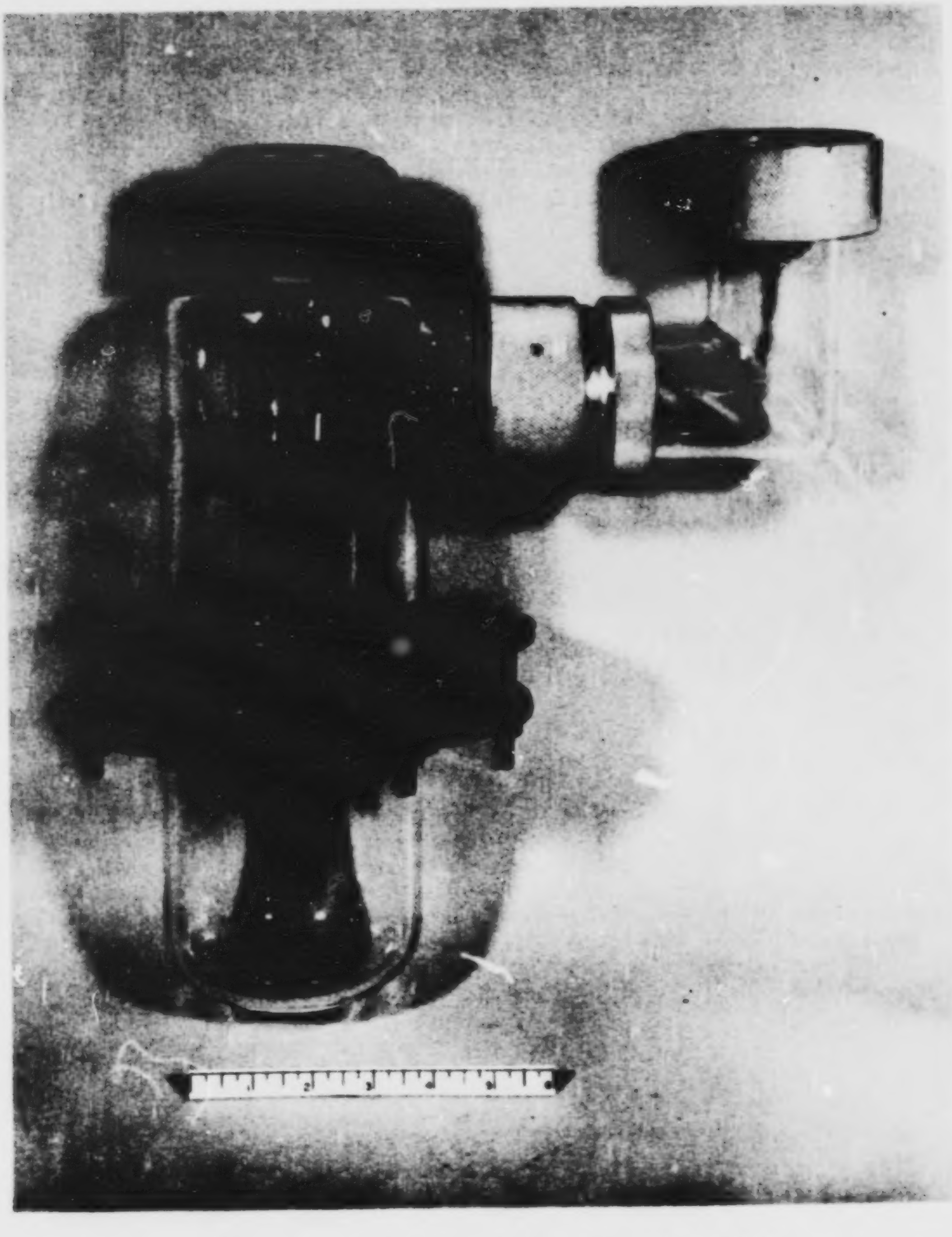


Figure 6. Concentric Return Assembly Used in Silting Experiments (Scale is in inches)

EXPERIMENTAL RESULTS

AERATION STUDIES

Four hundred ten (410) test runs were performed to evaluate the aeration characteristics of the pilot-scale U-tube. Not all of the instrumentation discussed in the previous section was included from the first run, e.g., the third dissolved oxygen probe was not available before Run 139. In general, instrumentation was added as the value of additional measurements became apparent.

A summary of the tests, including an outline of the system parameters and measurements which were made, is shown in Table 1. Appendix A contains the experimental data acquired for Runs 1 through 94 (using the center-plug aspirator). Appendix B contains all data for runs using the venturi aspirator. It should be noted that Appendix B also contains other information which was generated from the experimental data using the data reduction program which will be described in the Analytical Studies section. Table 1 and Appendix B explain which of the values are experimental data and which are calculated values. The two sets of values are combined in Appendix B for the convenience of the user.

Figures 7 and 8 illustrate typical trends of the test data. In these two figures, the applicable oxygen transfer data have been adjusted to a standard set of conditions (the original data had varying inlet D.O. and some variations in temperature and ambient pressure) so that they can be plotted meaningfully. The abscissa on each graph is the amount of oxygen supplied in mg/l. This quantity is directly related to the initial air-to-water volume ratio:

$$\begin{aligned} \text{Oxygen supplied, mg/l} &= 2.80\ (\text{air/water at } 14.7\text{ psia, } 68°\text{F}) \\ &= 2.63\ (\text{air/water at } 13.8\text{ psia, } 68°\text{F}) \end{aligned}$$

It can be seen that the exit D.O. concentration increases, although with a decreasing rate of increase, as the amount of oxygen supplied is increased. Although not obvious from Fig. 7, the curves will not be asymptotic to the saturation concentration (9.08 mg/l) because of the ability of U-tube systems to raise the D.O. level above the ambient saturation concentration, if designed for such high exit D.O. levels. As the water velocity is decreased, the exit D.O. concentration increases and the overall pressure drop decreases; therefore, the experimental results clearly illustrate the advantages of low water velocities in system performance. There are trade-offs, however, when the system economics are considered, since lower velocities require larger capital expenditures. This will be further discussed in the later section on Application Studies.

TABLE 1

SUMMARY OF MEASUREMENTS MADE IN U-TUBE AERATION EXPERIMENTS

Run Numbers	Aspirator Type	U-Tube Depth (ft-in.)	Water Depth Above Aspirator Inlet (in.)	Dissolved Oxygen Measurements			Pressure Measurements		
				Aspirator Exit	U-bend Exit	Platform	Aspirator Exit	U-bend Entrance	Platform
1-25	center-plug	36-9	6 & 12						
26-94	center-plug	45-0	12				x	x	
95-138	venturi	45-5	7				x	x	
139-167	venturi	45-5	7	x			x	x	
168-219	venturi	18-10	7	x			x	x	
220-252	venturi	8-11	7		x		x	x	
253-263	venturi	8-11	7				x	x	
264-318	venturi	27-11	7			x	x	x	
319-325	venturi	27-11	7				x	x	
326-410	venturi	36-6	7		x		x	x	x

The following measurements were made for all runs: water temperature at entrance and exit, water flow rate, air flow rate, ambient pressure, ambient air temperature, D.O. at entrance and exit, and overall head loss across the system.

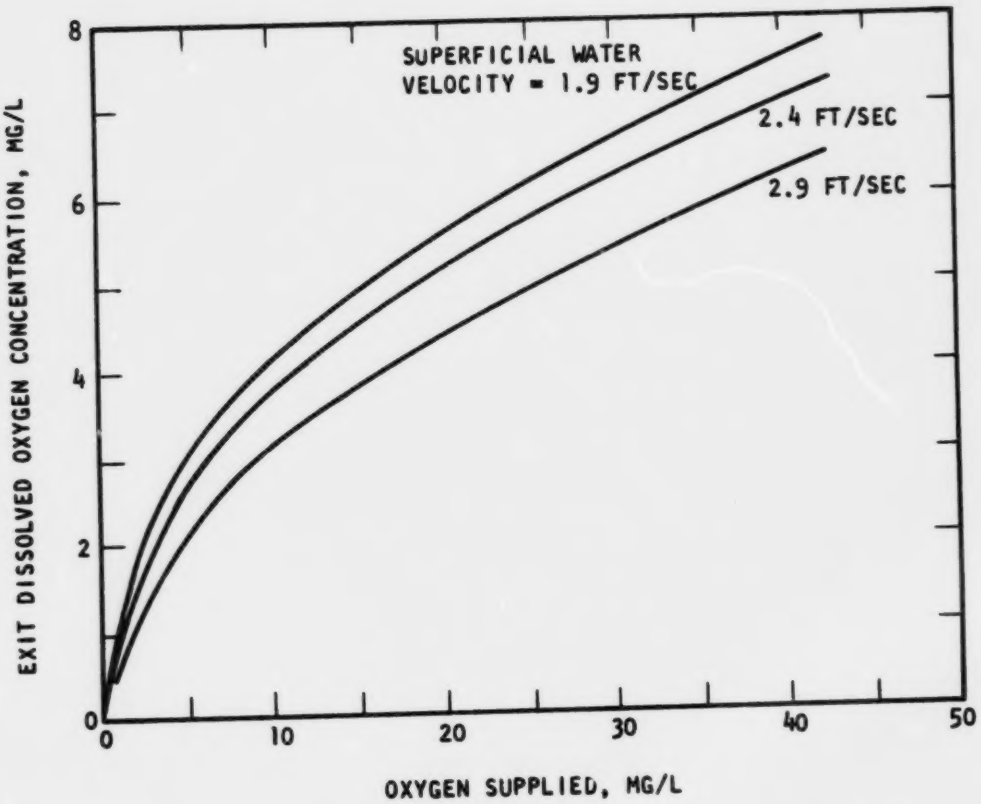


Figure 7. Dissolved Oxygen Increase Across 28-ft Deep Experimental U-Tube (reduced to standard conditions of 68° F, 1 atm, zero inlet D.O.)

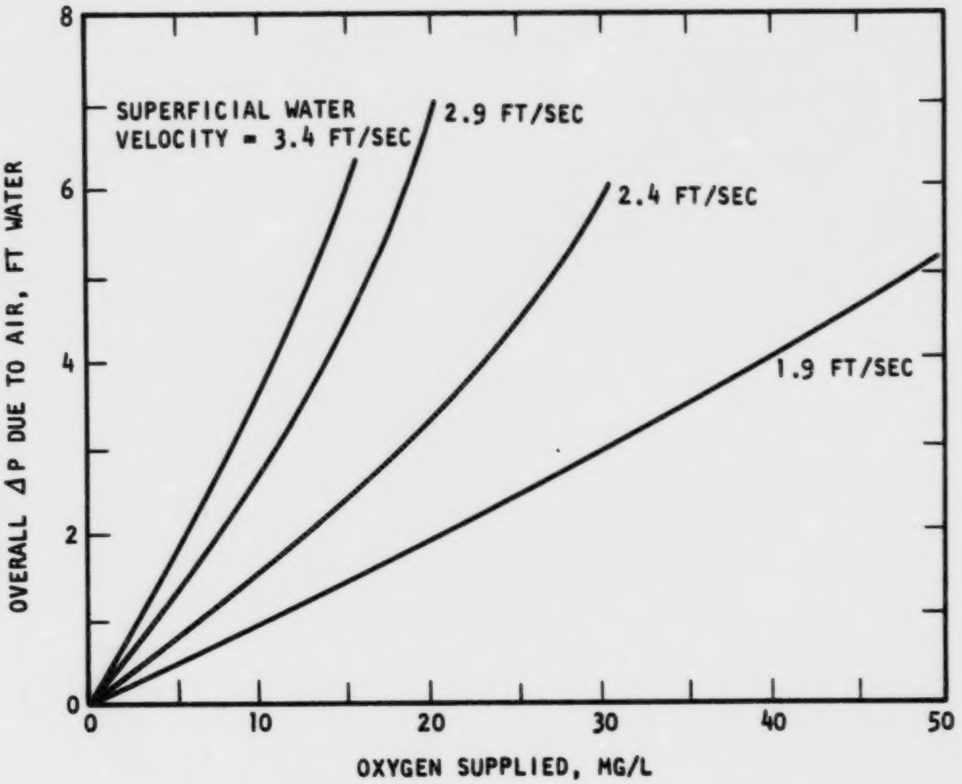


Figure 8. Overall Pressure Drop Due to Air Across 28-ft Deep Experimental U-Tube

ASPIRATOR EVALUATION

It was noted soon after the beginning of experimentation that permanent pressure losses across the center-plug aspirator were quite large. Since the oxygen transfer efficiency of the system is directly related to this loss, design began early on an improved (venturi) aspirator. It was apparent soon after installation that the venturi design was markedly superior.

A comparison of pressure drop between the two units was first made using water. A series of runs was made with the center-plug aspirator at fixed contraction ratios and variable water flowrate (Runs 73-94). Similar data were available from several sets of runs with the venturi. A plot of the permanent pressure loss vs water velocity for the two aspirators is shown in Fig. 9 for several values of contraction area ratio, E (defined as cross-sectional area of pipe divided by minimum flow cross-sectional area in aspirator). It is apparent that the pressure loss for the venturi aspirator (which has a fixed E of 8.0) is approximately equal to the pressure loss for the center-plug aspirator with the contraction ratio set at 2.9. It was possible to obtain a given amount of aspiration with the venturi aspirator at a much lower permanent head loss than with the center-plug aspirator. Another advantage of the venturi aspirator concept is that the minimum dimension of the flow passage remains higher than for a center-plug aspirator, thus reducing the chance of plugging.

AIR BUBBLE CHARACTERIZATION

High-speed motion pictures were taken of the two-phase fluid flow during nine runs with each type of aspirator in a U-tube 45-ft deep. These pictures were used in determining various air bubble characteristics. A random sample of approximately 25 bubbles in each of several frames was used for determining bubble shapes, sizes, and slip velocities for each run. Measurements were made from projected enlargments of the motion pictures.

Figures 10, 11, and 12 show enlargements of six frames, selected at random, from the motion pictures for Runs 131, 136, and 137. In each figure, the top photograph shows a section in the U-tube located approximately 7 ft below the aspirator outlet (the flow direction is from top to bottom), and the bottom photograph shows the glass return bend (with flow from right to left). It can be seen that the air bubbles are approximately oblate spheroids, with larger bubbles generally having greater eccentricity than small bubbles. There is some observable flattening of the bubble leading surfaces as compared with the trailing surfaces; however, this is not a large effect except for the largest bubbles.

Table 2 summarizes the results for runs with the venturi aspirator. The pictures taken during runs with the center-plug aspirator, as well

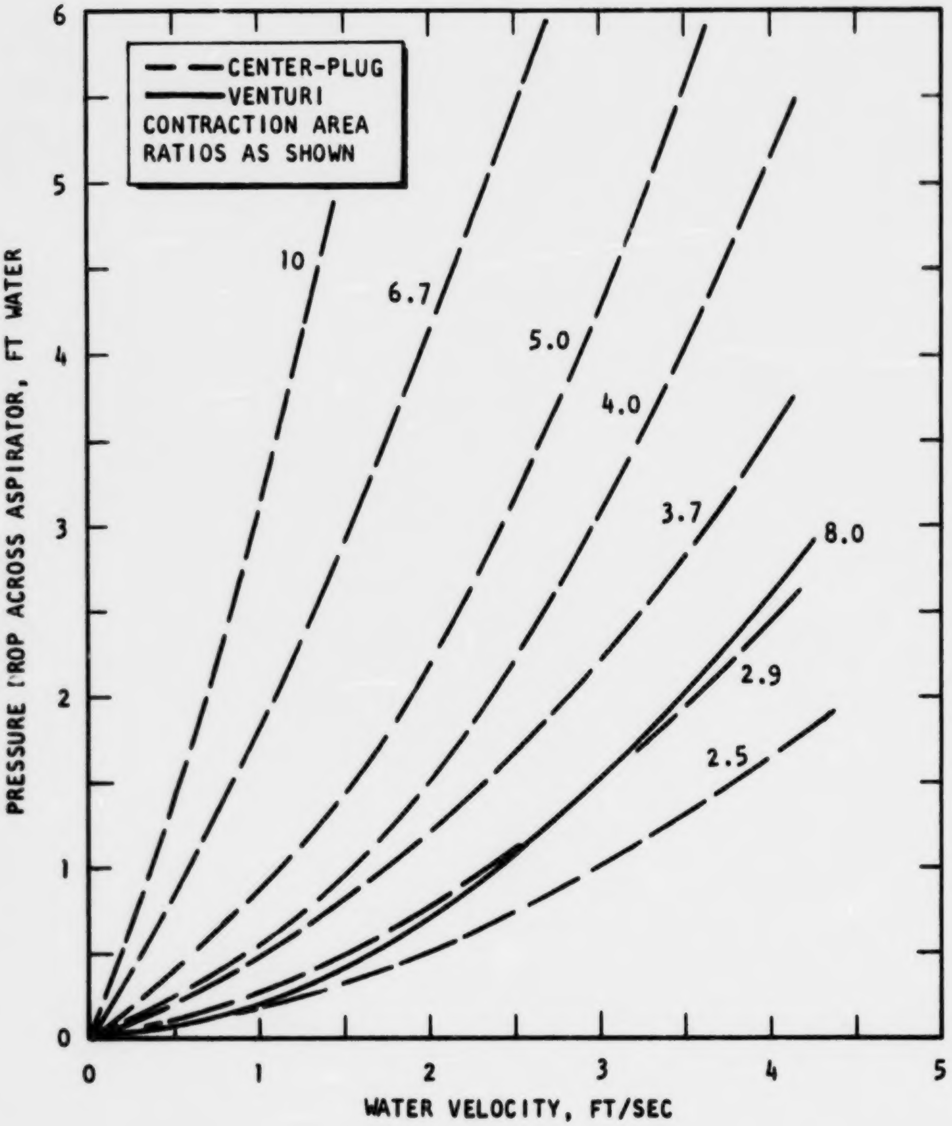
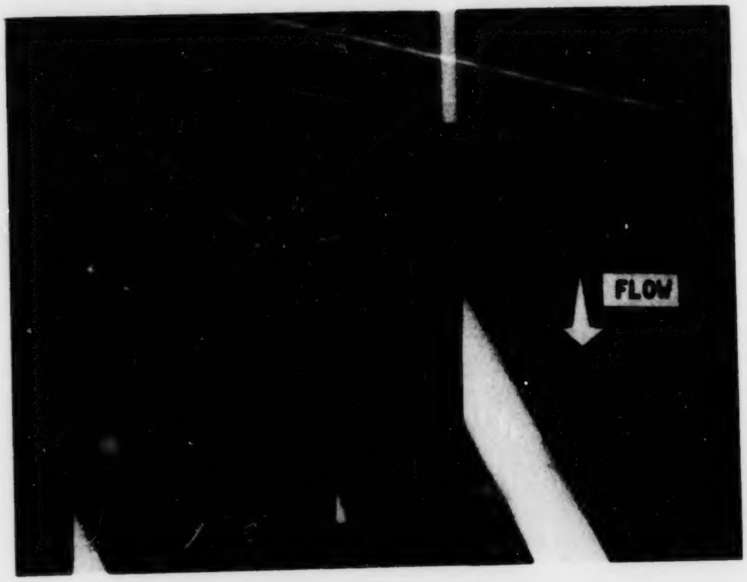


Figure 9. Comparison of Pressure Drop Across Center-Plug and Venturi Aspirators



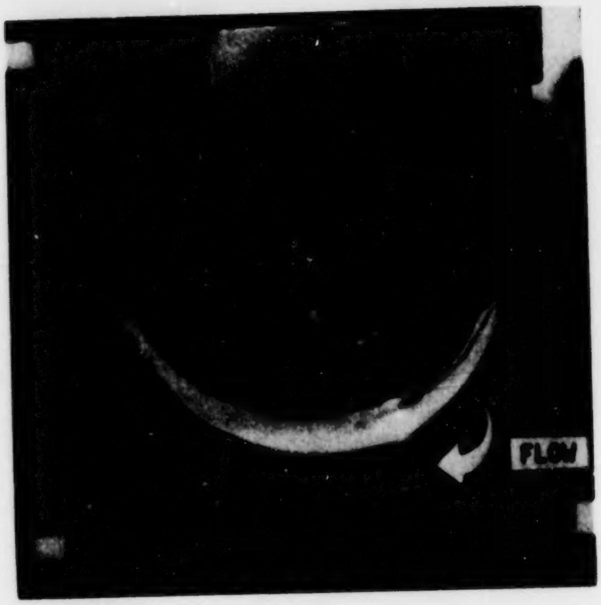


Figure 10. Photographs of Two-Phase Flow in U-Tube (Run 131, superficial water velocity = 2.9 ft/sec, initial air/water volume ratio = 0.014 at 1 atm, 68° F

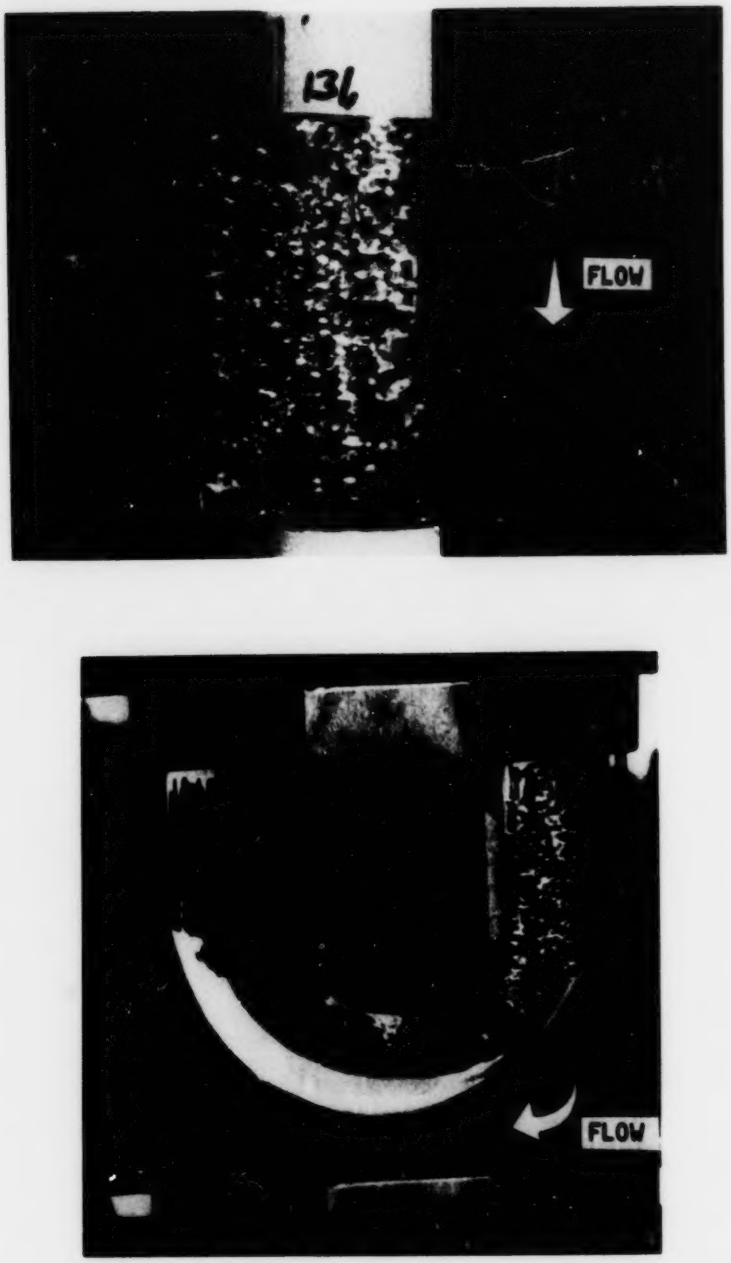


Figure 11. Photographs of Two-Phase Flow in U-Tube (Run 136, superficial water velocity = 2.4 ft/sec, initial air/water volume ratio = 0.063 at 1 atm, 68° F

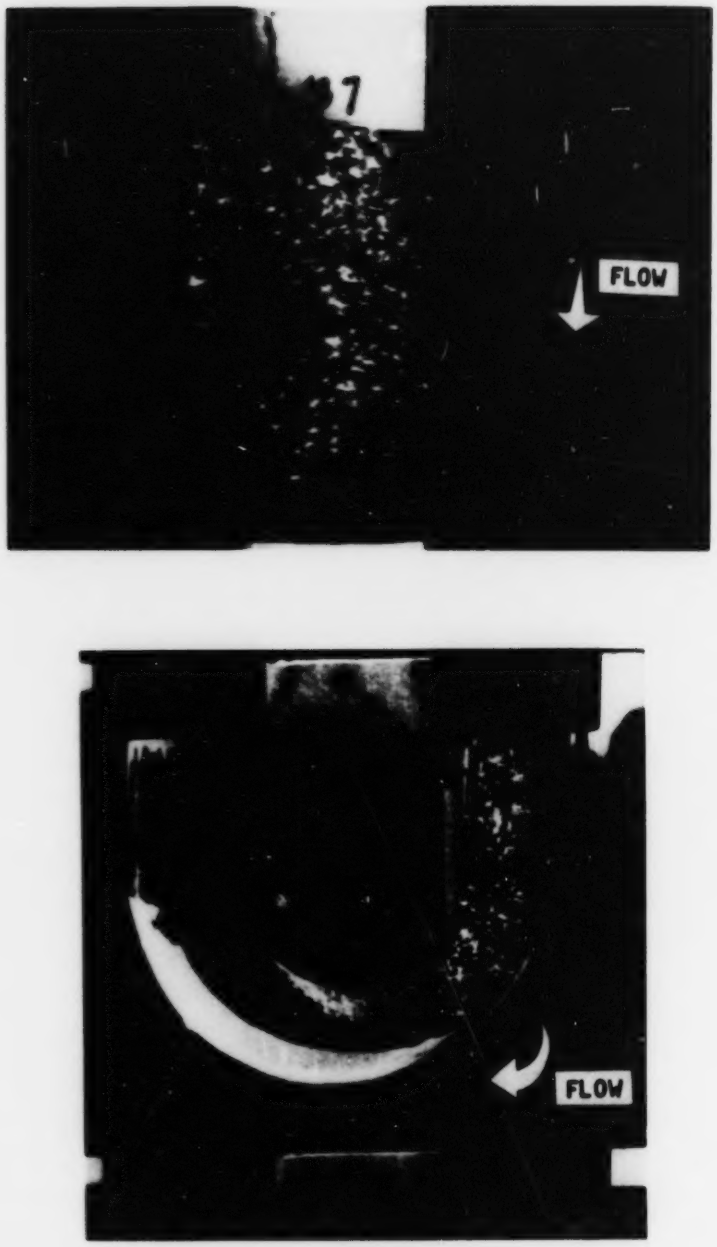


Figure 12. Photographs of Two-Phase Flow in U-Tube (Run 137, superficial water velocity = 2.0 ft/sec, initial air/water volume ratio = 0.088 at 1 atm, 68° F)

TABLE 2

SUMMARY OF TWO-PHASE FLOW CHARACTERISTICS IN U-TUBE WITH VENTURI ASPIRATOR

Number	Superficial Water Velocity (ft/sec)	Initial Air/Water Volume Ratio at 1 atm, 68°F	Location in U-tube	Bubble Mean Major Diameter (inch)	Bubble Mean Major/ Mean Minor Diameter	Total Area/ Bubble Volume (inch^{-1})	Mean Slip Velocity (ft/sec)
131	2.9	0.014	top bottom	0.18 0.18	0.53 0.55	39.8 39.2	0.08
132	2.4	0.046	top bottom	0.17 0.17	0.61 0.52	40.2 41.3	0.19
133	2.0	0.066	top bottom	0.19 0.20	0.53 0.53	40.2 36.0	0.24
134	1.9	0.022	top bottom	0.21 0.20	0.47 0.47	29.7 42.9	0.20
135	2.8	0.039	top bottom	0.20 0.19	0.46 0.45	40.4 45.6	0.23
136	2.4	0.067	top bottom	0.23 0.20	0.46 0.49	26.3 37.6	0.01
137	2.0	0.094	top bottom	0.19 0.19	0.59 0.48	37.8 42.3	0.23
138	2.8	0.045	top bottom	0.19 0.19	0.54 0.47	39.8 41.7	0.20
Mean values for eight runs			top bottom	0.19 0.19	0.52 0.50	36.9 40.8	0.17

as Run 130 with the venturi aspirator, were of poorer quality than the later eight runs represented in Table 2; therefore, the information from these eight runs was used as the primary basis for characterizing the two-phase flow. The superficial water velocity is, as previously defined, the velocity with which the water would flow at the measured flow rate if the air were not present. The initial air-to-water volume ratio expresses the amount of air introduced in the aspirator before any gas is dissolved. The "top" location in the U-tube was a section located approximately 7 ft below the aspirator outlet in the ten-foot length of glass pipe. The "bottom" location was about six inches above the bottom of the glass return bend section. The mean diameter values given in Table 2 are arithmetic mean values of the approximately 50 to 75 randomly chosen bubbles for each case (i.e., approximately 25 bubbles chosen from each of 2 or 3 frames). The ratio of mean major diameter to mean minor diameter is given because it has greater statistical validity than the mean of the individual ratios for each bubble. The total air-water interfacial area per unit volume of air, X, is the variable actually used in later analytical studies to characterize the effects of bubble size and shape on the mass transfer. It was calculated by summing the values of interfacial area divided by bubble volume for each individual bubble in a run (treating the bubbles as oblate spheroids with the measured major and minor diameters) and dividing by the total number of bubbles measured for that run. This variable thus combines the effects of bubble size and shape distribution, and is not a function of the absolute bubble population or air-to-water ratio. It can be seen from the results in Table 2 that there is no apparent effect of water velocity or air-to-water ratio on the bubble shapes or sizes. Even more surprising, however, is the absence of a difference in bubble size between the top and the bottom of the U-tube, a distance of 36 ft. If most of the bubbles remained as discrete entities throughout their passage through the down-leg, there would be a detectable change in mean bubble size between the top and bottom. Apparently, there is enough net bubble coalescence to compensate for the increase in pressure (plus some small amount of gas dissolution). The balance of these two effects may not be neutral in other physical situations; however, the pilot-scale U-tube with venturi aspirator and 45-ft length seems to be characterized by approximately constant air bubble size throughout at least the down-leg.

Slip velocity is defined as the difference between the actual (not superficial) water and bubble velocities, i.e., $u_s = u_w - u_a$. It is an important parameter in the evaluation of mass transfer coefficients through the U-tube. With this definition the slip velocity is positive in the down-leg and negative in the up-leg. The slip velocity values are inherently less accurate than the other experimental data because the possible error in determining both water velocity and bubble velocity is large with respect to their difference (slip velocity). It was not possible to obtain meaningful slip velocities at the return bend because of the flow curvature there.

Figure 13 shows the experimental slip velocities at the top of the downleg for the venturi and center-plug aspirators. The data for the center-plug aspirator show more scatter than the venturi aspirator data, which is reasonable since the latter were taken from pictures with greater magnification, hence, improved definition. In spite of the scatter, the data suggest a mean slip velocity of about 0.2 ft/sec, especially in the case of the venturi aspirator. The slip velocity appears to be independent of water velocity or air-to-water ratio over the ranges of variables included in these two-phase flow tests.

NITROGEN TRANSFER

Procedures and apparatus for the analysis of dissolved gases have been discussed in the Experimental Studies section. The results for the four samples (i.e., entrance and exit samples for Runs 293 and 375) are shown in Table 3.

TABLE 3

RESULTS OF CHEMICAL ANALYSIS FOR DISSOLVED NITROGEN

Run Number	293	375
Superficial water velocity (ft/sec)	1.9	1.4
Air/water at 1 atm, 68°F	5.8	7.0
D.O. concentration (mg/l):		
entrance	2.2	1.1
exit	7.4	5.6
D.N. concentration (mg/l):		
entrance	3.8	2.6
exit	16.8	12.9
D.N. change/D.O. change	2.5	2.3

It can be seen that the D.O. concentrations in Table 3 disagree somewhat with the meter readings for entrance and exit D.O. (Appendix B). This discrepancy is thought to be due primarily to errors in the sampling and analytical procedures. The significant results are the ratios of D.N. change to D.O. change. These ratios were used in estimating nitrogen mass transfer coefficients from the oxygen mass transfer coefficients determined from the experimental aeration runs.

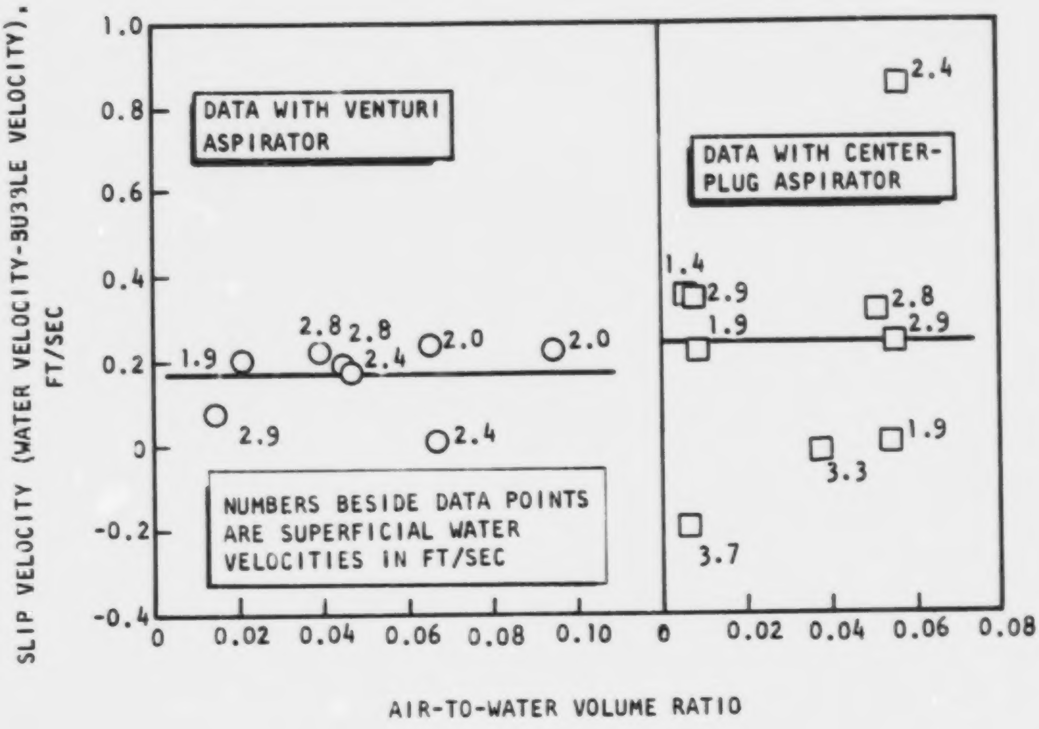


Figure 13. Air Bubble Slip Velocities Near Top of U-Tube

SILTING STUDIES

The objective of the silting-scouring studies was to develop a basis for designing U-tubes so that they would be free from plugging problems due to silting. The experimental results and other studies conducted in accomplishing this objective are described in the following paragraphs and Appendix C.

The first portion of Appendix C contains a brief description of some relevant physical factors and a summary of some previous experimental studies in this area. Relatively few applicable studies were found in the limited literature search which was conducted. No work was found which investigated silting or scouring in vertical or curved pipes, which are the cases of interest in a U-tube.

Brief experimental studies were conducted as a part of this project. The experimental procedures for the silting studies were discussed in the Experimental Studies section. The experimental data and information are given in Appendix C. One difficulty in evaluating and applying the scouring data was the uncertainty in defining and evaluating values for scour velocity (i.e., that minimum velocity necessary to cause settled particles to dislodge from the solid bed and be transported into the up-leg of the U-tube). Figure 14 illustrates the concentric return bend assembly used in the experiments (a photograph of the assembly was previously given in Fig. 6). It was realized that a non-uniform velocity profile existed in a direction perpendicular to the solid bed surface. Since it was not possible to determine the actual surface velocity (which would be a most reasonable definition for scour velocity), the scour velocity was defined as the average water velocity through the area formed by an imaginary cylinder extending from the down-leg bottom to the solids bed surface (see Fig. 14). The scour velocities were evaluated at constant water flowrate by determining the distance B at which solids ceased to be removed from the solid bed at the bottom of the return bend. With the depth of scour and U-tube ΔH as data, average scour velocities were determined for each particle size.

A series of scour depth and U-tube head loss measurements were taken for each test run (see Appendix C). Head loss measurements enabled evaluation of water velocity from a series of calibration runs. The scour velocity was determined at each depth of scour, and an average was taken for the run. Velocities showing large deviations from the average (usually at the start of a run) were discarded. The results are as follows:

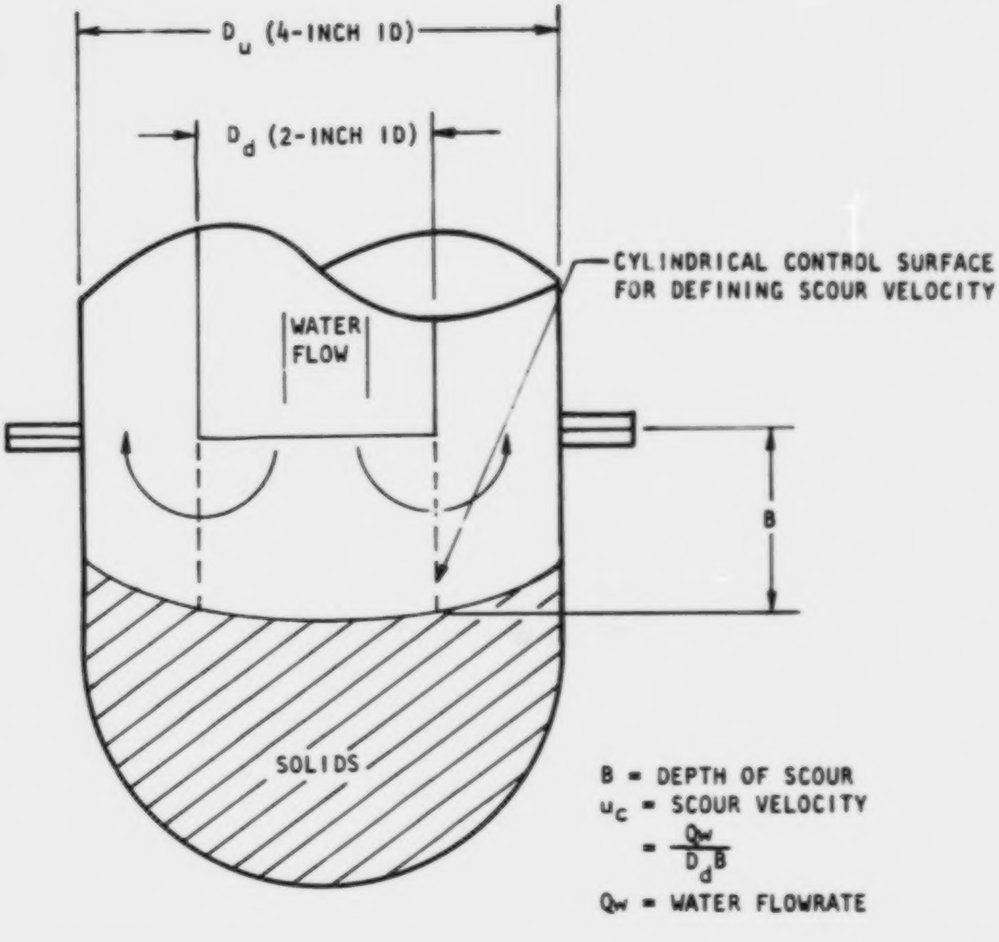

D_u (4-INCH ID)
D_d (2-INCH ID)
CYLINDRICAL CONTROL SURFACE FOR DEFINING SCOUR VELOCITY
WATER FLOW
B
SOLIDS
B = DEPTH OF SCOUR
u_c = SCOUR VELOCITY
= Qw / D_d B
Qw = WATER FLOWRATE

Figure 14. Diagram Illustrating Analysis of Experimental Scour Data

Particle Size Range (mm)	Number of Determinations	Range of Scour Velocity (ft/sec)	Average Scour Velocity (ft/sec)
4.00 - 5.66	6	0.39 - 0.42	0.40
2.00 - 2.38	10	0.29 - 0.32	0.31
1.00 - 1.41	5	0.23 - 0.25	0.24
0.50 - 0.60	5	0.20 - 0.21	0.20

These data are represented by curve 6 in Fig. 15. This particular curve in Fig. 15, it should be remembered, is a representation of scour velocities of a particular concentric return bend at the bottom of a U-tube for particles in the range 0.50 to 5.66 millimeters. Caution should be used in extrapolating the results beyond this particle size range or to different systems. However, the results do give some basis for determining velocities necessary to keep a U-tube return bend free of solids with diameters less than 1/4-in.

Other relationships for velocities required to scour or prevent silting are also plotted in Fig. 15 (curves 1 through 5). These relationships are explained in Appendix C. It can be seen that there are considerable differences between the data obtained herein and predictions from various sources. The fact that the required velocities from this investigation are lower than the others plotted in Fig. 15 is due at least partly to the definition of scour velocity used in this case. The actual velocity at the bed surface was undoubtedly higher than the average velocity (based on a constant velocity profile across the flow cross-section at the minimum point) which was used to calculate the values given in the above table and in Fig. 15.

Despite the divergence in the relationships for determining safe velocities which will avoid sedimentation, it is still possible to design U-tubes which are practical, yet which should be free of silting. Of the relationships illustrated in Fig. 15, it is judged that design velocities selected from approximately the range recommended by curve 5 should be used to prevent sedimentation in the bottom of a U-tube. Thus, it should be possible to prevent sedimentation of sand and rock particles up to the size of fine gravel by designing a U-tube for minimum water velocities of approximately 1.5 to 3 ft/sec. The experimental results of this investigation suggest that these may be rather conservative. This is a very practical requirement for a U-tube application; therefore, preventing sedimentation in a U-tube system is not expected to be a serious design problem.

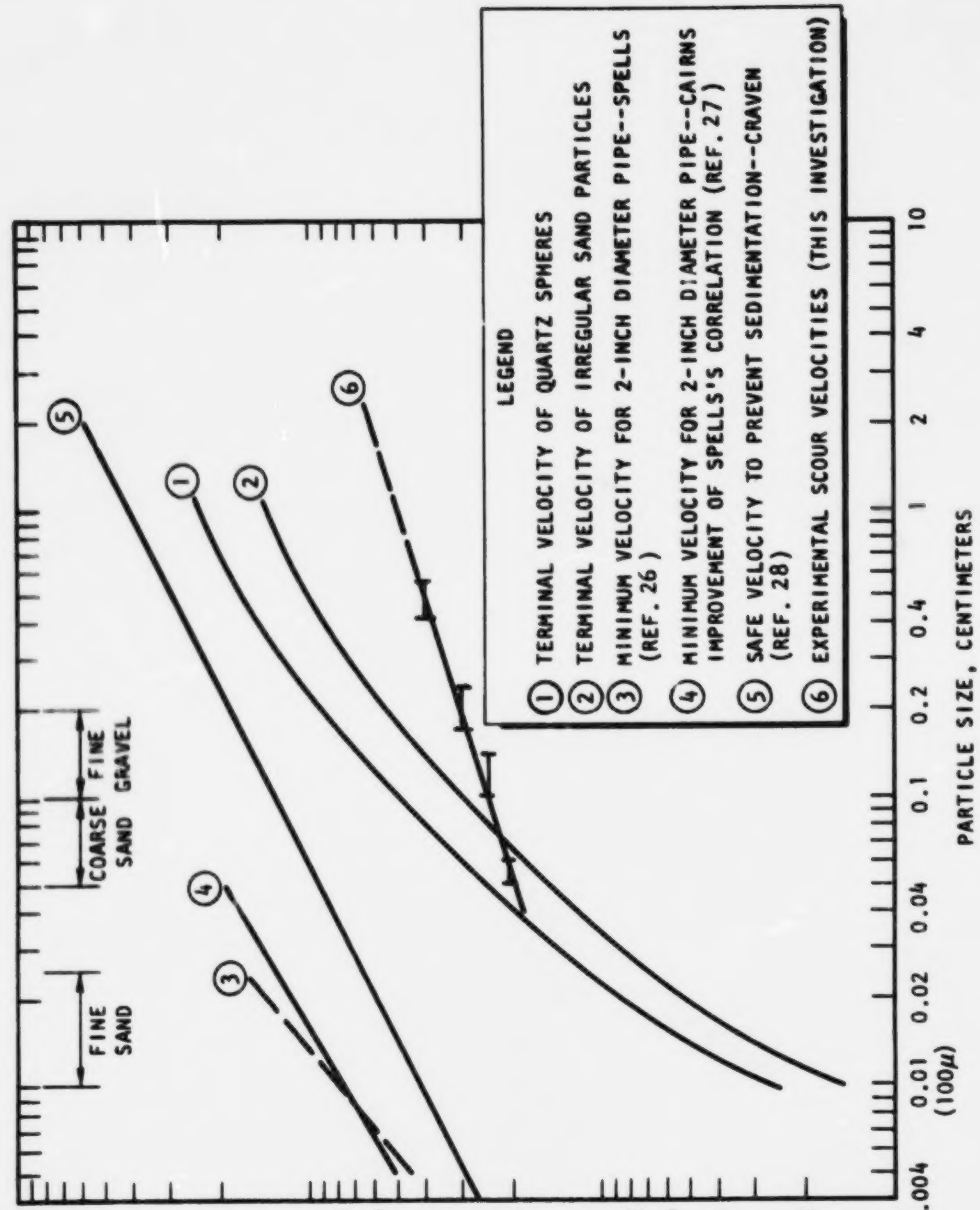


Figure 15. Effect of Particle Size on Scour Velocity

ANALYTICAL STUDIES

The basic elements of a U-tube aeration system are: (1) a unit for introducing air (or oxygen) into a flowing water stream, followed by (2) two connected vertical conduits through which the air-water mixture flows down and back up, thus giving a substantial residence time in a region of above-ambient pressure. The device for introducing air could be one of several types of aspirators (in which air is induced by a local high velocity, low pressure region in the flowing water stream), or the device could be some type of diffuser through which compressed air in injected.

In addition to the type of device for introducing air, there are numerous variations in configuration, relative sizes of system components, and operating conditions which may be considered for each type. This variety of possibilities, and the complexity of the physical processes occurring within a U-tube system, makes it not very satisfactory to present the experimental results in terms of graphs or equations giving overall oxygen transfer for various combinations of U-tube geometry, size, and operating variables. Similarly, the widely used "figure-of-merit" -- weight of oxygen transferred per unit of power expended (e.g., lb oxygen/hp-hr) -- can be very misleading if used to compare different types of aeration systems, since amortized capital costs and other expenses can also be very significant. Representative values of lb oxygen/hp-hr are given in Appendix B, together with the experimental and derived data.

The primary goal of the analysis performed during this study was to develop a general design basis for predicting mass transfer and pressure loss characteristics for various U-tube systems under wide ranges of operating conditions. The following sub-sections describe generalizations of the experimental results, and analytical models which were developed, first to calculate mass transfer coefficients from the experimental data and finally to perform design computations for various types of U-tube systems. Both the complexity of the physical phenomena and the limitations of the current state-of-the-art in describing many of them, necessitated heavy reliance upon generalizations from the experimental data obtained during this project.

The mass transfer in a U-tube system is strongly dependent upon the air bubble size and shape distribution; therefore, the bubble measurements described earlier were made. The effects of the changing static pressure throughout a U-tube system were considered in the modeling. The transfer of nitrogen was considered as well as the transfer of oxygen; both the mass transfer and hydraulic characteristics are affected by the relative velocities of the water and air. This factor, also, was evaluated from experimental results.

The task of predicting or modeling fluid flow, specifically the prediction pressure changes, centered primarily in three sections of a U-tube system: the air inlet device, the down-leg, and the up-leg. Each is a separate and difficult problem. These are not entirely tractable analytically; therefore, experimental results were also used in developing prediction and design bases. The resulting relationships will be presented in the following sub-section.

GENERALIZED EXPERIMENTAL RESULTS

One of the important efforts of the program was the development of relationships from the various experimental results. Areas of major interest were characterization of the venturi aspirator in terms of permanent pressure drop and mass transfer coefficient, U-tube down-leg pressure loss, and U-tube up-leg pressure loss. Generalized mass transfer coefficients for the U-tube are discussed in a later subsection, "Results from Data Reduction Program".

Venturi Aspirator Pressure Drop

Equations were developed to predict the permanent pressure loss across a venturi aspirator. These were based on the one- and two-phase data generated during this project, plus applicable data and information found in the literature. The final relationship was used in the design computer program. It was not necessary to employ the predictive equation for aspirator pressure drop in the data reduction program, since this pressure drop was measured for all runs.

The initial efforts in developing an equation to predict venturi aspirator pressure drop involved an approximate theoretical treatment. It was assumed that the loss is composed of four additive components:

1. Single-phase wall friction loss
2. Gas-liquid interfacial friction loss
3. Loss due to momentum exchange in the mixing region
4. Loss due to compressing the gas from the low pressure at the throat to the higher pressure at the venturi exit.

Single-phase loss was very consistent for all runs, and equal to approximately 17 percent of the throat velocity head (the throat velocity head was approximately equal to the pressure differential between the inlet and the throat with the 8:1 area ratio venturi used). This value was determined from experimental measurements for single-phase flow, and it agrees well with the predicted single-phase permanent head loss for typical Herschel venturies (10 to 20 percent of the pressure differential betewen the inlet and the throat). The gas-liquid interfacial frictional losses could not be evaluated theoretically. Estimates were made of the loss due to momentum exchange, but gross assumptions were necessary concerning the shape of the interface between the water and the air-water mixture downstream of the air inlet. Pressure loss due to gas compression was calculated from the ideal gas law assuming isothermal compression. This amounted to a maximum of 5 percent of the total head-loss observed.

The theoretical predictions were compared with the experimental data developed during this project for head loss across the venturi. These data are plotted as a function of air-to-water ratio and water flowrate in Fig. 16. It can be seen that the data for all velocities seem to be approximately linear for lower air-to-water ratios; however, the data for 1.9 ft/sec demonstrate a definite decrease in slope for higher values of air-to-water ratio. The comparison of the initial theoretical predictions with these data showed considerable discrepancies in some regions. Since it was beyond the scope of the present project to develop the theoretical analysis further, it was decided to modify it and develop a more empirical correlation of the form:

$$\Delta p = c_1 \; (y)^{c_4}(u_{th})^{c_3} + c_2(u_{th})^2 \qquad (1)$$

The first term represents the single-phase frictional losses. Analysis of the single-phase losses fixed c_2 as 0.0026, with Δp in ft of water and u_{th} in ft/sec.

Two alternate expressions were derived for the two-phase loss term. The more limited expression, based on a linear correlation (i.e., $c_4 = 1$) of the head loss vs air-to-water ratio data in Fig. 16 resulted in the equation

$$\Delta p = 0.007y \; u_{th}^{2.84} + 0.0026 \; u_{th}^{2} \qquad (2)$$

where Δp is the permanent pressure loss (ft of water) u_{th} is the superficial water velocity at the venturi throat (ft/sec), and y is the air-to-water volume ratio, expressed at 1 atm and 68°F. This equation represents the experimental data fairly well up to approximately the following maximum air-to-water ratios:

Superficial Water Velocity in Pipe u (ft/sec)	Superficial Water Velocity at Throat u_{th} (ft/sec)	Maximum y
3.4	26.9	0.04
2.9	23.1	0.06
2.4	19.2	0.10
1.9	15.3	0.10
1.4	11.6	0.10

A more general expression for the venturi pressure loss was desired, particularly one which would be usable for air-to-water ratios in the range 0.10 to 0.20. A search of the literature uncovered two sets of

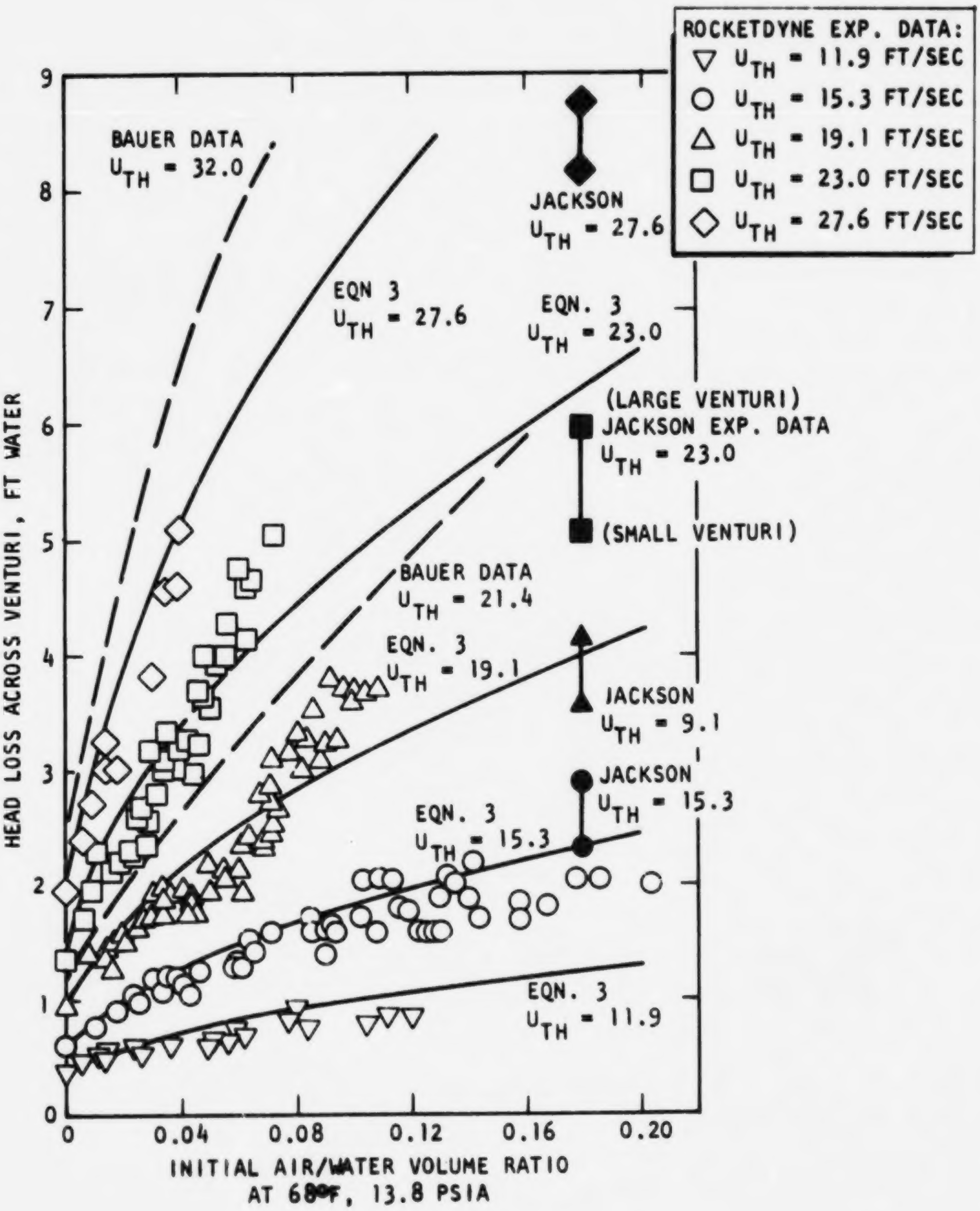


Figure 16. Two-Phase Pressure Drop Across Venturi Aspirators

data on venturi aspirators. Jackson's data[7,8] are for two venturi sizes and with air and water. Bauer's data[9] are for carbon dioxide and water, but should still be comparable, assuming that no large amount of carbon dioxide was dissolved within the actual venturi (since the venturi was rather small, this is probably not a bad assumption). These additional data are also plotted in Fig. 16. The data could not be plotted directly since neither the throat velocity nor the air-to-water ratio was held constant. The data were first plotted as a function of throat velocity, since the gas-to-water ratios were nearly constant. A slight arbitrary adjustment of the resulting curves to account for the small changes in y gave curves from which head loss could be read as a function of throat velocity for constant y. Values were read from this intermediate curve and plotted in Fig. 16 for comparison and adjunction with the experimental data obtained during this project.

It can be seen that the data from Rocketdyne, Jackson, and Bauer are in fair agreement, although there is, understandably, scatter within and between the sets of data. The Jackson data show larger pressure drops for the larger venturi, although this may be due to small differences in hardware design rather than scale effects.

After consideration of alternative general equations to represent the combined three sets of data, the final equation selected was

$$\Delta p = 0.004\ (y)^{0.6}\ (u_{th})^{2.6} + 0.0026\ (u_{th})^2 \qquad (3)$$

in which Δp is the total head loss across the venturi aspirator, in ft of water; u_{th} is the single-phase or superficial water velocity at the venturi throat, in ft/sec; and y is the air-to-water volume ratio at the venturi entrance, expressed at 1 atm and 68° F. This equation is plotted for several values of u_{th} in Fig. 16, and was used in the design computer program which will be described in a later section.

Venturi Aspirator Mass Transfer

Mass transfer coefficients were evaluated for the venturi aspirator from the experimental data obtained during this project. Coefficients were defined by the basic transport equation:

$$\frac{dC}{dt} = K_L a\ (C_s - C) \qquad (4)$$

where C is the local concentration of dissolved oxygen, t is time, "a" is the air-water interfacial area per unit volume of two-phase fluid, C_s is the local saturation value for dissolved oxygen concentration, and K_L is the liquid-phase mass transfer coefficient. Integration of the above equation, assuming constant C_s, gives

$$tK_L a = \ln\left(\frac{C_s - C_4}{C_s - C_5}\right) \qquad (5)$$

where the subscripts 4 and 5 refer to the venturi throat and diffuser exit, respectively. The liquid residence time in the diffuser was taken as V/Q, where V is the diffuser volume and Q is the fluid volumetric flowrate. C_4 and C_5 were measured venturi inlet and exit D.O. levels (Runs 139-219). With a specific assumption about how to evaluate a "mean" value of C_s (at some "mean" diffuser pressure), the overall mass transfer coefficient, K_La, was evaluated from the expression

$$K_La = \frac{Q}{V} \ln \left(\frac{C_s - C_4}{C_s - C_5}\right) \tag{6}$$

No attempt was made to evaluate K_L alone since the effective mean value of "a" was not determinable. It was also not possible to separate the effects of oxygen transfer during bubble formation from transfer in the remainder of the aspirator diffuser.

Jackson concluded that the majority of the mass transfer occurred in his venturi aspirators after considerable pressure drop had been recovered.[7] Accordingly, C_s was evaluated at a pressure corresponding to 3/4 of the distance from the throat to the diffuser exit. It was shown that evaluating C_s half-way down the diffuser or at the diffuser exit shifted the calculated coefficients by less than ± 6 percent. The dissolved oxygen saturation data of Montgomery[10] were used, together with Henry's law to evaluate C_s at various temperatures and pressures. K_La was also corrected to 20° C by the expression

$$\frac{(K_La)_{20}}{(K_La)_T} = (1.024)^{20-T} \tag{7}$$

where T is the experimental water temperature in degrees Centigrade.

The calculated coefficients are shown in Fig. 17 as a function of superficial water velocity, u_w, and air-to-water ratio, y. It is apparent that below $y = 0.04$ the scatter is severe, whereas above $y = 0.04$ the trend of K_La as a function of flow rate becomes readily discernible. The severe scatter below 0.04 is due to high percentage errors in both the air flowrate and the dissolved oxygen measurements at low air-to-water ratios. The resulting dependence of K_La upon y_o° (initial air-to-water ratio expressed at 1 atm and 68° F) and u_w (superficial water velocity in pipe) or on y_o° and Q (water flowrate) can be represented within about ± 3 percent by the equations:

$$\begin{aligned} (K_La)_{20} &= 3.84\, y_o^\circ\, Q^{2.85} \\ (K_La)_{20} &= 3000\, y_o^\circ\, u_w^{2.85} \end{aligned} \tag{8}$$

where K_La is in hr^{-1}, Q is in gpm, and u_w is in ft/sec.

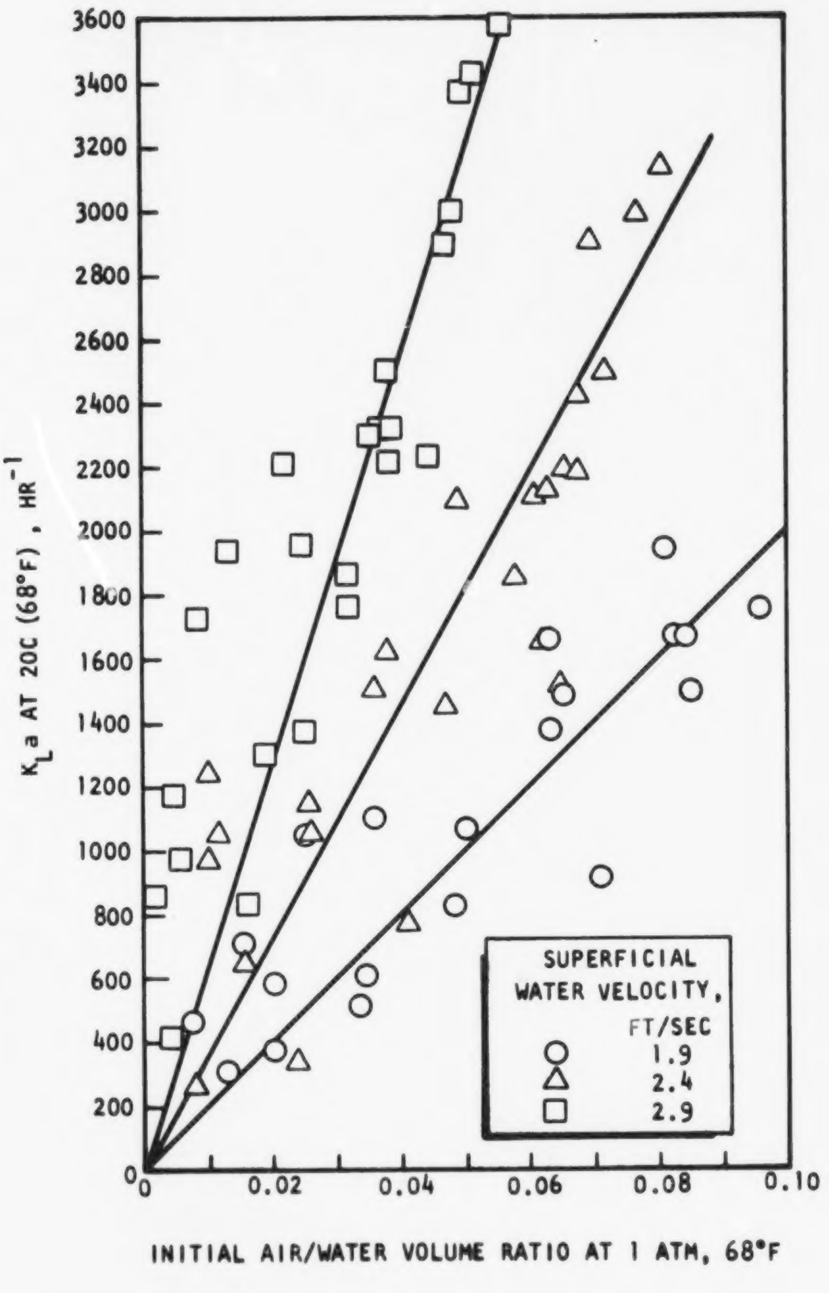


Figure 17. Experimental Mass Transfer Coefficients for Venturi Aspirator

Down-Leg Pressure Loss

A literature search located several references pertinent to the phenomenon of vertical two-phase flow. Unfortunately, all of the correlations which were presented pertained to slug flow or higher air-to-water ratio flow regimes. It is apparent from Fig. 5 that extrapolation of empirical results across regime boundaries is meaningless. Therefore, it was necessary to develop a correlation for down-leg pressure drop with bubble flow from the U-tube data.

The data were initially evaluated in terms of pressure loss per foot for each of the five U-tube lengths and were plotted against air-to-water ratio at standard conditions. Figure 18 shows typical data (for the 28-ft U-tube). Figure 19 shows the experimental data curve-fits for all five U-tube depths. It is apparent that head loss varies linearly with air-to-water ratio, y, over the range of y investigated. Furthermore, no functionality with respect to water flowrate is apparent. It is known that the single-phase losses are not the same at different water flowrates; therefore, a step discontinuity exists at $y = 0$ between the single-phase losses and the linear two-phase loss curves.

The effect of pipe diameter on two-phase pressure loss was desired to permit use of these results in general design predictions. Other data were required for this extension. The only useful data found were in a thesis by Adams,[11] which reports experimental work with a 4-inch diameter compressed-air U-tube at various depths. From Adams' data on total U-tube pressure losses and up-leg pressure recoveries, down-leg pressure losses were developed for U-tube lengths of 10, 20, 30, and 40 feet. Adams' data were for a superficial water velocity of 3.7 ft/sec, which was slightly greater than the maximum velocity (3.4 ft/sec) investigated on this program. Since no water velocity dependency was found from this study up to 3.4 ft/sec, it was assumed that this trend is also valid to 3.7 ft/sec.

The single-phase losses were first subtracted from the total down-leg pressure loss data for the two-inch U-tube used in the current project. Since Adams' data were for pipe lengths of even multiples of 10 feet, the pressure drop data for the two-inch U-tube nearest to each of Adams lengths were appropriately corrected for length. Air-to-water ratios were evaluated at column midpoint pressures to minimize any effect of changes in bubble size due to different absolute entrance pressures. The resulting corrected two-inch pipe losses were plotted along with Adams' four-inch pipe losses against air-to-water ratio, as shown in Fig. 20. It is apparent that the pressure losses due to air are indeed the same for the two systems when appropriate corrections are made. The curves agree very well for all lengths except 10 ft, where relative experimental errors (in measuring Δp) were probably the greatest for both systems.

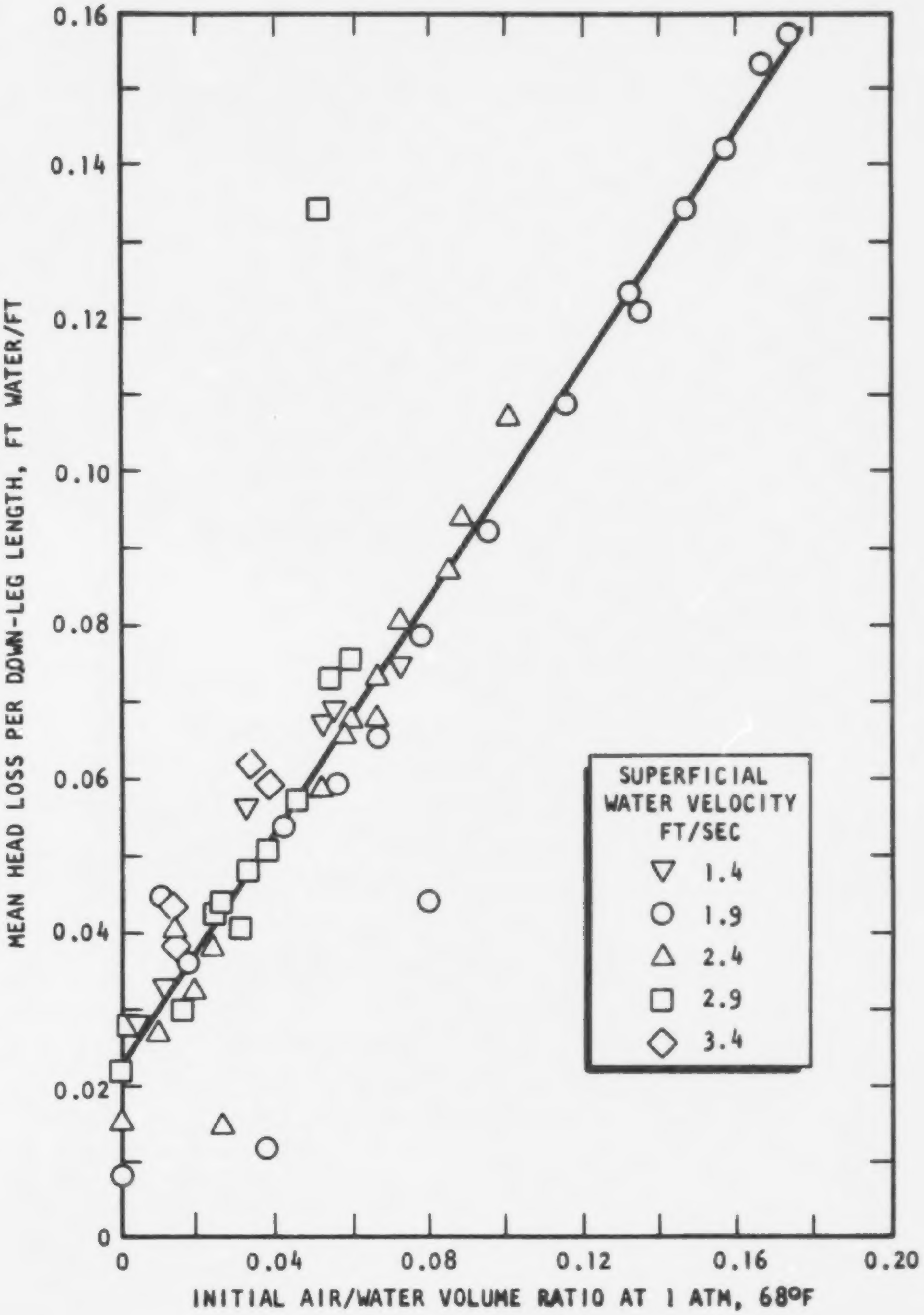


Figure 18. Experimental Down-Leg Head Loss Data for 28-ft U-Tube

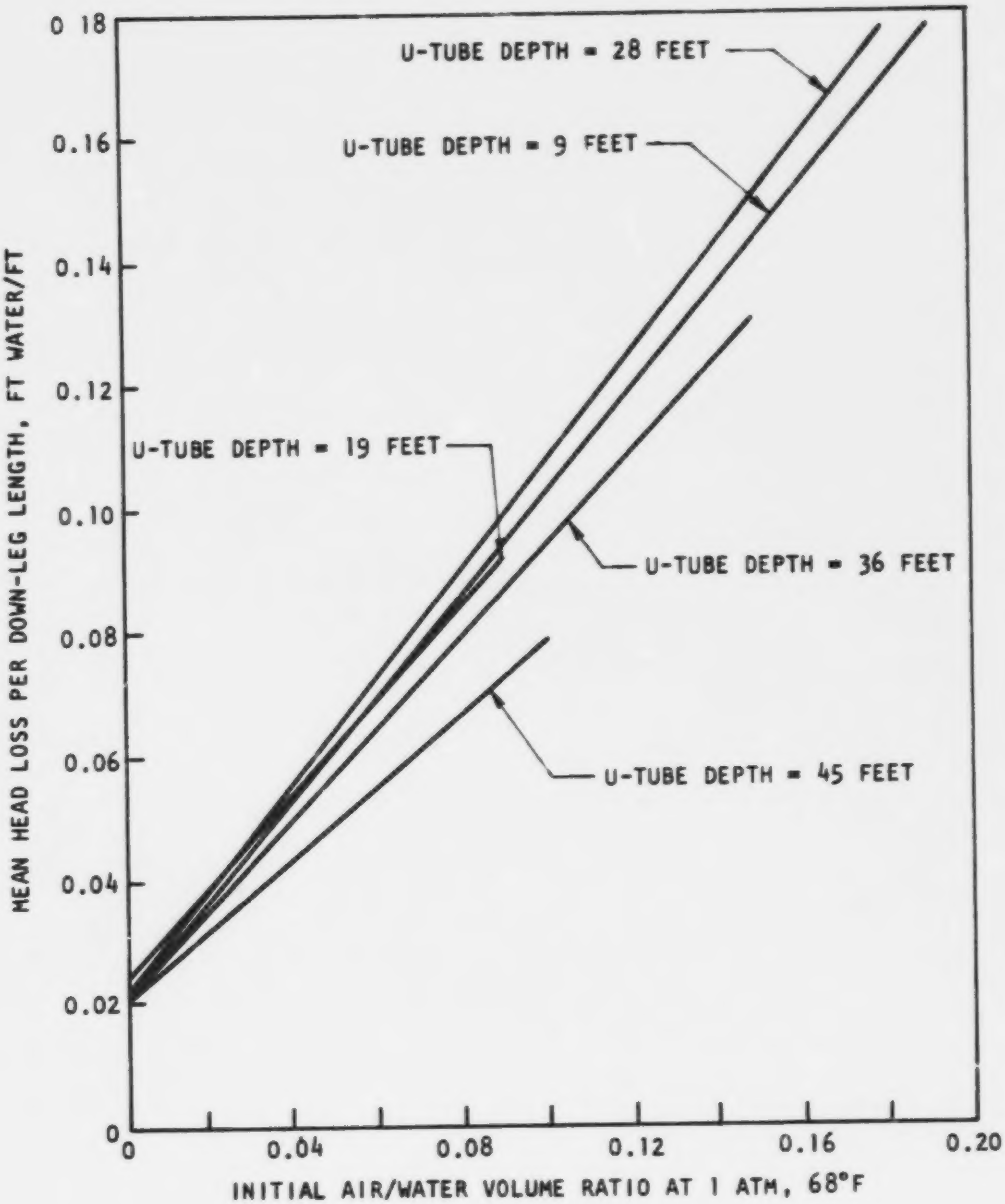


Figure 19. Experimental Down-Leg Head Loss for Various U-Tube Depths

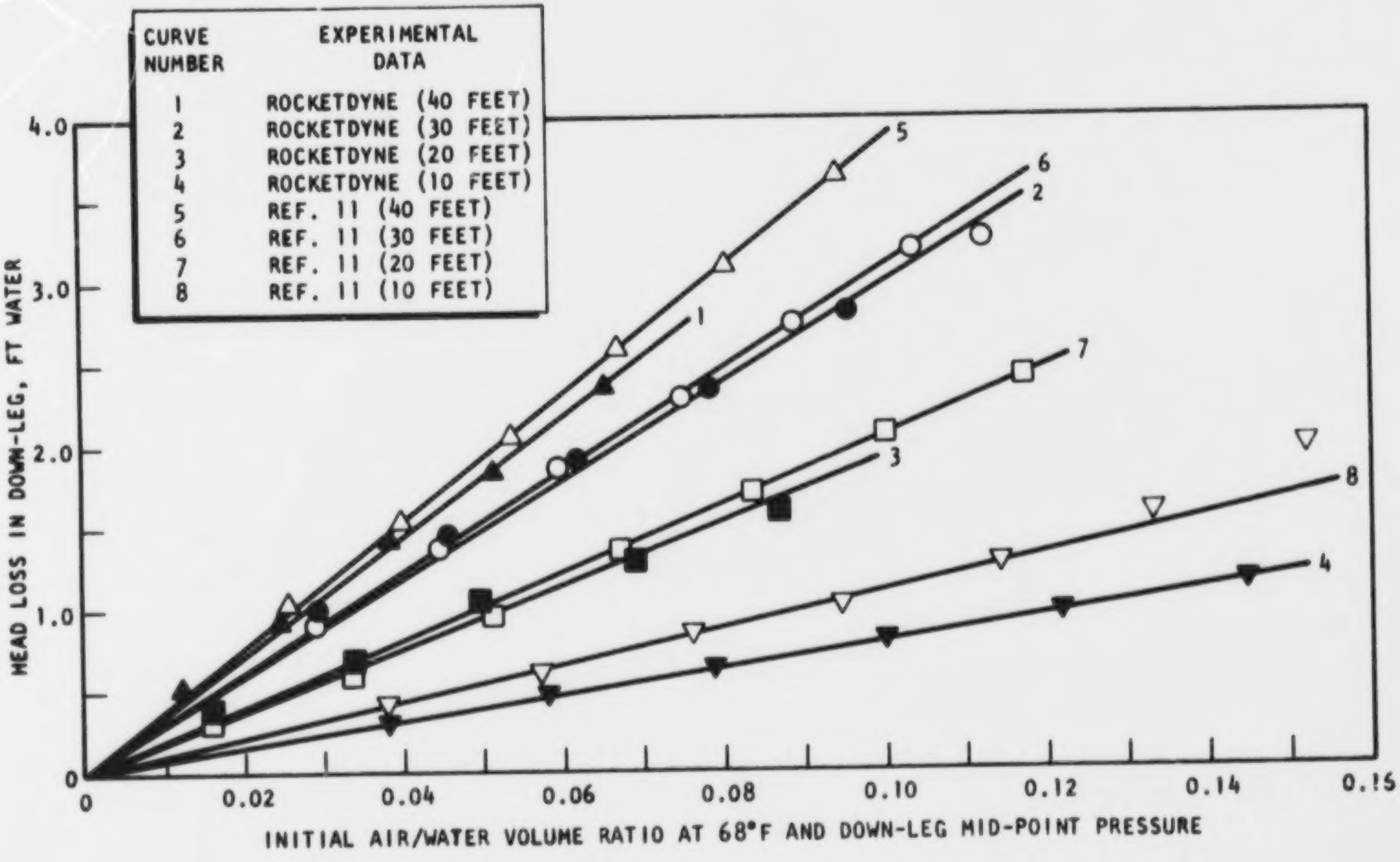


Figure 20. Down-Leg Head Loss Due to Air

It was concluded that down-leg pressure losses for any pipe size greater than two-inch diameter can be represented as

$$\Delta p_t = \Delta p_1 + \Delta p_2 = \Delta p_1 + c_5 y L \qquad (9)$$

where Δp_1 is the single-phase loss term, which can be calculated from the Fanning Equation, Δp_2 is the two-phase loss term evaluated from the two sets of data, and L is the down-leg length. The calculated constants for the two sets of data are:

L (ft)	c_5 for 2-inch Pipe (this study)	c_5 for 4-inch Pipe (Adams' study)
10	0.795	1.107
20	0.962	1.030
30	0.971	1.030
40	0.905	0.966

Assuming the error in c_5 to be relatively large at 10 feet and neglecting these values, the mean value for both sets of data is $c_5 = 0.98$, with fairly good agreement. The final equation is

$$\Delta p_t = \Delta p_1 + 0.98\ y\ L \qquad (10)$$

where the head losses are in ft of water, L is in ft and y is evaluated at the down-leg midpoint pressure. One remaining problem is the velocity to be used in evaluating the single-phase losses. Extrapolation of the curves in Fig. 19 to y = 0 suggests that 3 ft/sec is an acceptable velocity for this purpose, although this choice is empirical. In practice, though, a U-tube would usually be operated at air-to-water ratios of 0.1 or greater. Since the single-phase loss at this ratio is only about 20 percent of the total pressure loss, a small error in the total pressure loss is incurred regardless of the water velocity assumed to calculate the single-phase loss term.

Up-Leg Pressure Loss

Up-leg pressure gradient measurements were made only for the 37-foot U-tube. The average pressure differential per foot, F, is presented in Fig. 21 as a function of air-to-water ratio at standard conditions. It should be noted that F also includes the static pressure change, for reasons which will be apparent below.

The data scatter is great enough that direct correlation of the data did not appear fruitful in predicting the up-leg pressure gradient. Therefore, the Hershey correlation for the prediction of pressure gradients in airlift pumps was used.[12] It was judged that the correlation would be applicable to the up-leg of the U-tube, since similar two-phase flow conditions were involved. The correlation is

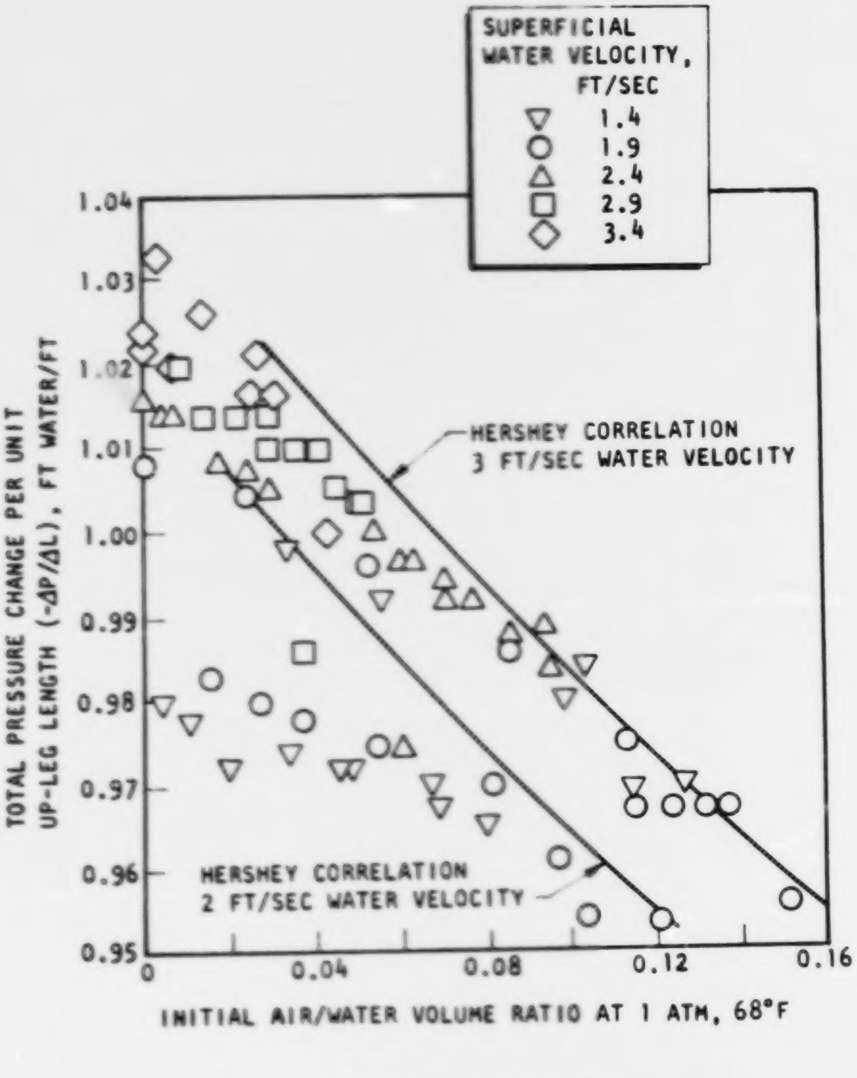


Figure 21. Experimental U-Leg Pressure Change Data and Hershey Correlation

(see Nomenclature section for definitions of symbols):

$$\frac{dp}{dL} = -\frac{\rho_w + 2\ f^*\ u_m^{\ 2}\ \rho_w/g_c D}{1 + y + \frac{\rho_w\ u_m}{g_c}\ \frac{du_m}{dp}} \qquad (11)$$

$$\frac{du_m}{dp} = \frac{4\ p_o\ u_a}{\pi\ D^2\ p^2}$$

$$f^* = 0.048(Re)^{-0.13}$$

$$Re = \frac{Du_m\ \rho_w}{u_w}$$

$$y = 3.5\ (Q_s D^{-2.5} gc^{-0.5})^{0.83} \qquad (12)$$

$$Q_a = Q_s + y\ Q_w \qquad (13)$$

The term dp/dL is the pressure loss or recovery per foot at local conditions, including the static head. Under U-tube flow conditions, the denominator can be simplified to 1 + y since the derivative term is small. The solution for dp/dL requires solving equations 11 through 13 simultaneously.

Predictions of up-leg pressure change were made using the Hershey correlation to evaluate F at various depths in the column, and then integrating F to yield the total pressure differential across the up-leg. The two curves shown in Fig. 21 were generated by dividing these integrated results for total pressure change by the up-leg length. It is apparent that the 2 and 3 ft/sec water velocity curves bracket the bulk of the data. Many of the points below the band of the two curves appear to be erroneous; some are for water velocities below 2 ft/sec.

As a further check on the utility of the Hershey correlations, a comparison was made of the predictions with Adams' data for 4-inch diameter pipe.[11] Adams reports only the two-phase pressure loss effects. The single-phase loss for 4-inch steel pipe at 3.7 fps was estimated to be 0.012 ft water/ft and was added to his two-phase recovery data. This correction enabled a common basis of comparison between the data and the Hershey correlation. The integrated form of the equation was used to develop the curves shown in Fig. 22. Adams reports linear pressure recovery with respect to the air-to-water ratio. The Hershey Equation predicts deviation from linearity. For the 30 and 40-foot lengths, the curves agree up to about y = 0.10. For the 10 and 20-foot lengths, the two sets of curves begin to diverge at lower values of y.

In summary, the Hershey correlation predictions agree quite well with, but are slightly more conservative (i.e., predicted head loss is slightly higher) than, the experimental data for up-leg head loss obtained during this project. On the other hand, the Hershey correlation

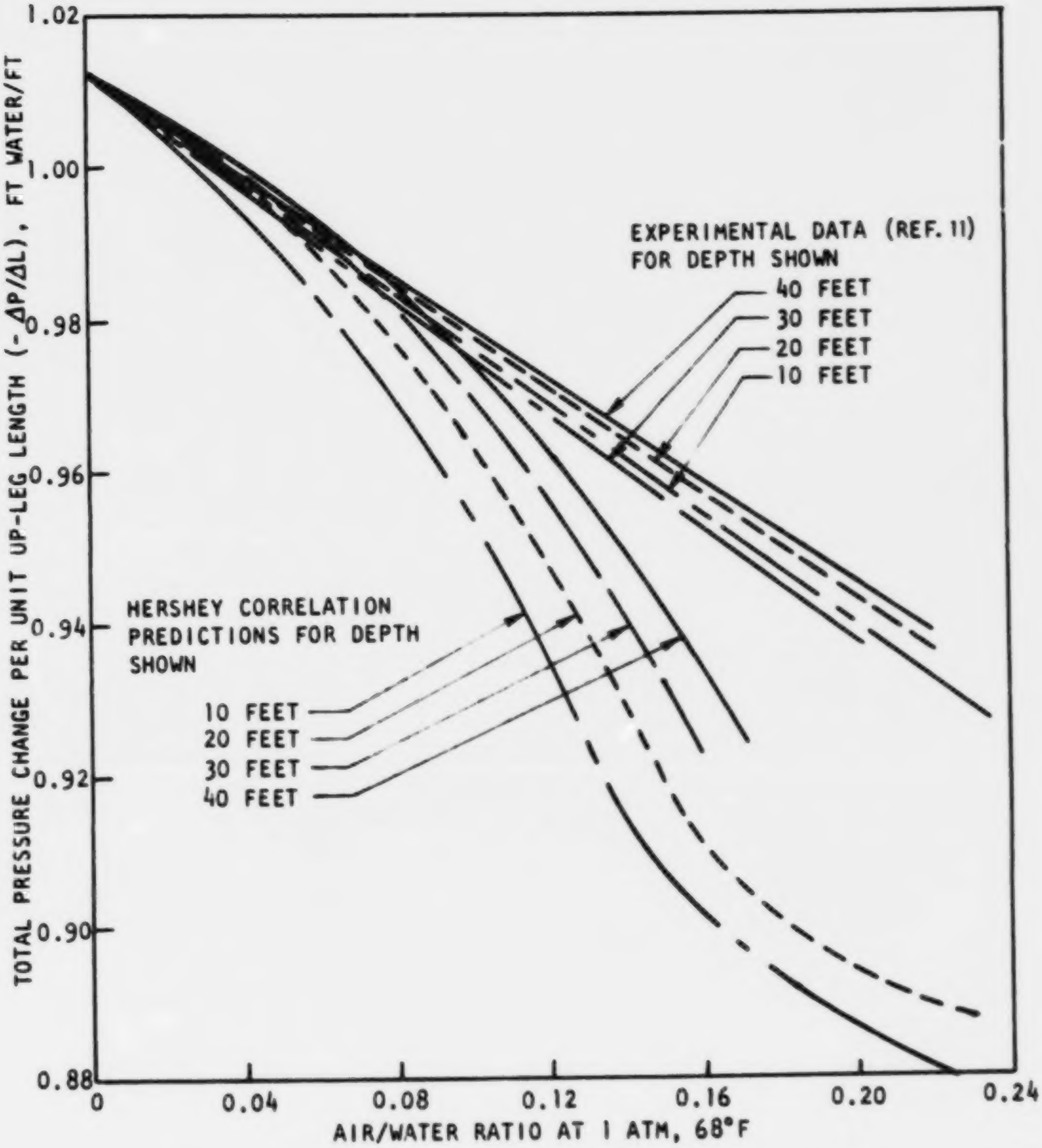


Figure 22. Adams' Experimental Up-Leg Pressure Change Data and Hershey Correlation

predictions begin to be less conservative than Adams' experimental data for air-to-water ratios above about 0.1. It was concluded that the Hershey correlation could and should be used for subsequent estimates of up-leg head loss.

DATA REDUCTION PROGRAM

A computer program was written to reduce the experimental data on aspirated-air U-tube oxygen transfer and pressure loss to a common basis, and to calculate values of a mass transfer coefficient. The experimental procedures and results have already been described in previous sections. In this section, the overall computation scheme used by the program will be outlined, then the detailed assumptions and relationships which were used in the program will be presented. Although this order of presentation reverses the actual order of development, this order should be more convenient for the reader.

Computation Outline and Program Description

The major components of the computation scheme built into the computer program are shown in the flowsheet of Fig. 23. It can be seen that the program estimates an initial value for the mass transfer coefficient, K_L, performs calculations thoughout the experimental U-tube system, compares the calculated exit D.O. concentration with the experimental concentration, and repeats the iteration until satisfactory agreement is reached. It was necessary to incorporate some sophistication into the iteration technique; simple iteration would not produce convergence in many cases.

The input variables are:

- run or identification number
- pipe diameter
- U-tube depth
- superficial water velocity (i.e., water velocity if flowing without air)
- air-to-water volume fraction
- ambient pressure
- water temperature
- inlet D.O. concentration
- outlet D.O. concentration
- static pressure at exit of aspirator, entrance of U-bend, and exit of system

The output variables are discussed in, and illustrated by, the output copies contained in Appendix B.

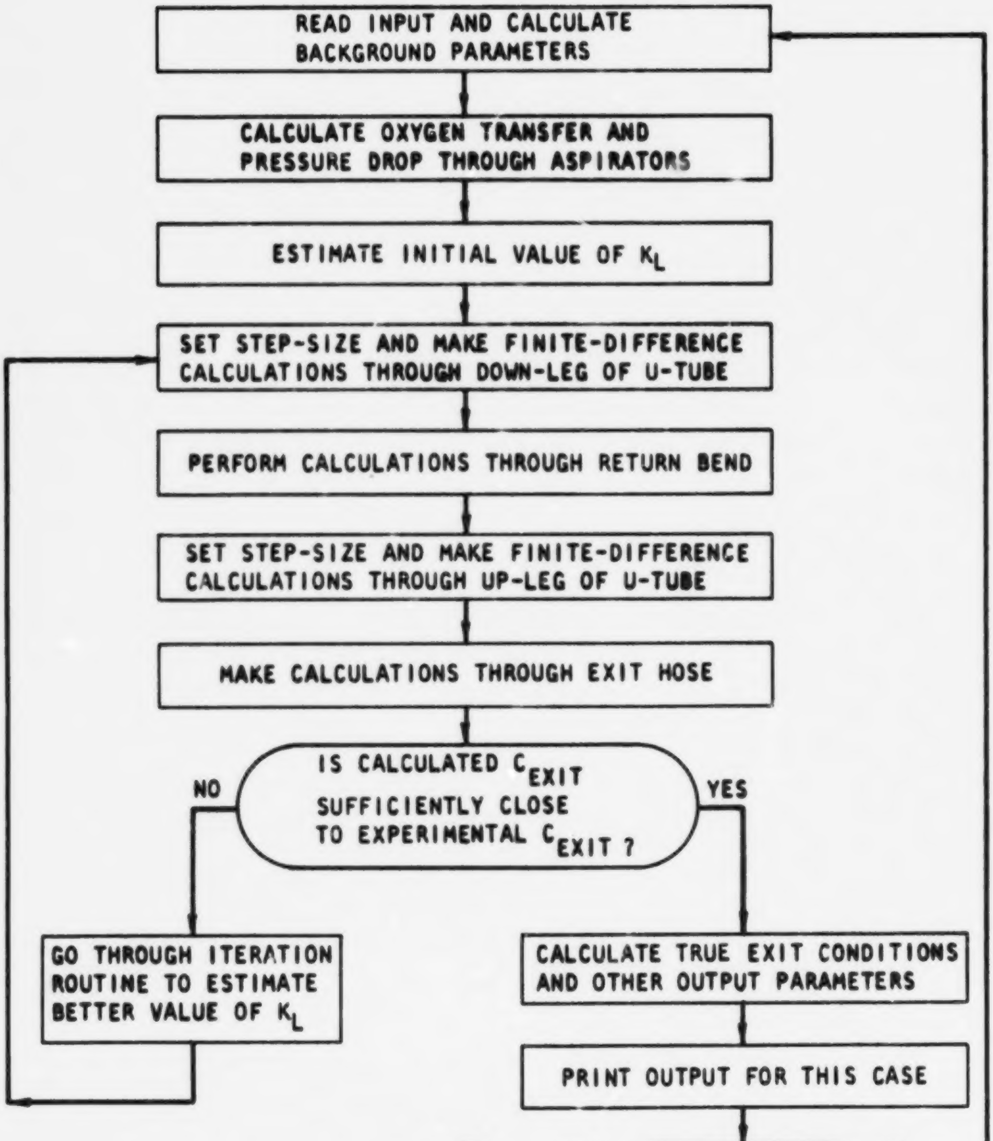

READ INPUT AND CALCULATE BACKGROUND PARAMETERS
CALCULATE OXYGEN TRANSFER AND PRESSURE DROP THROUGH ASPIRATORS
ESTIMATE INITIAL VALUE OF K_L
SET STEP-SIZE AND MAKE FINITE-DIFFERENCE CALCULATIONS THROUGH DOWN-LEG OF U-TUBE
PERFORM CALCULATIONS THROUGH RETURN BEND
SET STEP-SIZE AND MAKE FINITE-DIFFERENCE CALCULATIONS THROUGH UP-LEG OF U-TUBE
MAKE CALCULATIONS THROUGH EXIT HOSE
IS CALCULATED C_{EXIT} SUFFICIENTLY CLOSE TO EXPERIMENTAL C_{EXIT} ?
NO
YES
GO THROUGH ITERATION ROUTINE TO ESTIMATE BETTER VALUE OF K_L
CALCULATE TRUE EXIT CONDITIONS AND OTHER OUTPUT PARAMETERS
PRINT OUTPUT FOR THIS CASE
END
YES
LAST CASE FOR THIS RUN?
NO

Figure 23. Computation Flowsheet for Data Reduction Program

Important Relationships and Assumptions (Data Reduction Program)

Solubility data for oxygen in water at 1 atm air pressure (0.21 atm oxygen partial pressure) were taken from Ref. 10, and curve-fitted over the temperature range 50° to 85° F with the equation

$$C_s = 187.6\ T^{-0.714} - 0.16 \qquad (14)$$

with C_s in mg/l and T in degrees F. The solubility data for nitrogen in water at 1 atm nitrogen pressure were taken from Ref. 13, and curve-fitted over the temperature range 50° to 85° F with the equation

$$C_s' = 242.0\ T^{-0.6} + 0.07 \qquad (15)$$

with the same units as for equation 14 (superscript prime refers to nitrogen, while symbols without a superscript refer to oxygen). These data were adjusted to other pressures as required using Henry's Law.

Figure 1 showed a sketch of the U-tube experimental system with numbers assigned to various stations. In the following equations, numerical subscripts refer to values at a particular station.

In experimental runs for which D.O. concentration was measured at the aspirator exit, these values were used by the program. Where these values were not obtained experimentally, they were estimated using the relationship

$$C_5 = C_s - (C_s - C_1)\exp(-0.00104\ K_La/Q) \qquad (16)$$

where all concentrations are in mg/l, Q is the water flow rate in gpm, and K_La (in hr^{-1}) is given by equation 8, which was derived from the experimental runs in which the D.O. concentration at the aspirator exit was measured. Equation 16 is merely a specific version of equation 6, in which the diffuser volume is that of the venturi used in this project (0.00835 ft^3) and C_4 is replaced by C_1 (i.e., no oxygen transfer occurs upstream of the venturi). Equation 8 can be written, for K_La at any temperature T:

$$(K_La)_T = 3.84\ Q^{2.85}\ y_{\circ}^{\circ}\ (1.024)^{T-20} \qquad (17)$$

where $y_{\circ}^{\circ}$ is the initial air-to-water volume fraction, evaluated at standard conditions of 1 atm and 68° F, and T is water temperature in degrees C (note that T is almost always expressed in degrees F for dimensional equations in this report; however, this is an exception). Nitrogen transfer in the aspirator is calculated with a relationship analogous to equation 16, and with the assumption that K_La for nitrogen is the same as calculated from equation 17 for oxygen. The pressure at the aspirator exit was measured for all runs with the venturi aspirator (runs 95-410); therefore, these values were used in the program.

The calculations for a single distance step in the down-leg employed the following equations (i.e., given values at the end of step n, these equations were used to calculate values at the end of step n + 1). Symbols not already explained are defined in the Nomenclature section.

$$u_{m,n} = u_w(1 + y_n) \tag{18}$$

$$\Delta t_{a,n} = h/(u_{m,n} - u_s)$$

$$\Delta t_{w,n} = h/u_{m,n}$$

$$p_{t,n+1} = p_{t,n} - h\,F_n$$

$$C_{n+1} = C_n + K_L a_n (C_s - C)_n\, \Delta t_{w,n}$$

$$C'_{n+1} = C'_n + K'_L a_n (C'_s - C')_n\, \Delta t_{w,n}$$

$$n_{n+1} = n_n - K_L a_n (C_s - C)_n\, \Delta t_{a,n}/M$$

$$n'_{n+1} = n'_n - K'_L a_n (C'_s - C')_n\, \Delta t_{a,n}/M'$$

$$p_{n+1} = \frac{n_{n+1}(p_{n+1} - p_v)}{n_{n+1} + n'_{n+1} + n'_{i,n+1}}$$

$$p'_{n+1} = \frac{n'_{n+1}\ (p_{n+1} - p_v)}{n_{n+1} + n'_{n+1} + n_{i,n+1}}$$

$$y_{n+1} = \frac{p_{t,n}\, y_n}{p_{t,n+1}} - \frac{a_n\, \Delta t_{w,n}\, [K_L(C_s-C)_n + K'_L(C'_s-C')_n]}{\rho_{a,n+1}}$$

$$a_{n+1} = \frac{y_{n+1}\, X}{1 + y_{n+1}}$$

These equations apply for iteration steps in the down-leg, return bend, up-leg, or exit hose--with appropriate values for F, u_s, and X in each section. The change in pressure per unit length in the down-leg (F_d), was based on an empirical relationship derived from the experimental measurements of pressure at the aspirator exit and return bend. The value of F in the return bend was estimated from conventional fluid dynamics relationships, considering the two-phase velocity. The Hershey correlation was used to estimate values of F at each step in the up-leg, as discussed in the previous section on Generalized Experimental Results. The values of u_s and X, obtained from the motion pictures of two-phase flow in the experimental apparatus (as described in the Experimental sections), were $u_{s,d}$ = 0.2 ft/sec, $u_{s,u}$ = -0.2 ft/sec, and $X_d = X_u$ = 470 ft^{-1}.

The entering D.N. (dissolved nitrogen) concentration was assumed to be twice the measured entering D.O. concentration. The values of K_L' were estimated at 1.2 times K_L in accounting for nitrogen transfer in the system.

EXPERIMENTAL MASS TRANSFER COEFFICIENTS

The complete output from the data reduction computer program for experimental runs with a venturi aspirator is presented in Appendix B. The values of mass transfer coefficient are summarized in Fig. 24 through Fig. 28, plotted as functions of air-to-water ratio and for the five experimental U-tube lengths. Three of the major conclusions which can be drawn from the data are: (1) K_L is essentially independent of water velocity over the range 1.4 to 3.4 ft/sec (with respect to the results of this investigation); (2) K_L decreases slightly with increasing air-to-water ratio, except that the negative slope becomes quite large for air-to-water ratios less than about 0.04; (3) K_L decreases slightly with increasing U-tube depth. Limitations of experimental accuracy at small air-to-water ratios (less than about 0.03) raise some question about the validity of the results at very small ratios. At low ratios the air orifice manometer differential was very small, leading to possibly large air flow rate errors. Also, at low air-to-water ratios, the change in D.O. across the U-tube was small, leading to comparatively larger errors in the difference.

These mass transfer coefficient data were curve-fitted to form a generalized predictive equation for use in design. After considering the limitations on experimental accuracy and the fact that field installations would normally be designed for air-to-water ratios in the range 0.05 to 0.2, it was decided to curve-fit only the data for ratios above 0.04. A single parameter least-squares analysis was first performed on each set of data for a single U-tube depth, considering six different forms of a single parameter equation. The best single equation form for all five sets of data was

$$K_L = A_1 y^{B_1}$$

where A_1 and B_1 are constants. The best-fit equation in each case is plotted and written on the appropriate graph (Fig. 24-28).

The five individual equations of this form were then modified to yield a general expression for K_L as a function of air-to-water ratio and U-tube depth. The average value of A_1 for the five depths (0.00042) was assumed constant. A new exponent, B_2, was defined such that the value of K_L at an air/water ratio of 0.10 was the same for each depth as the value of K_L predicted with the least squares equation derived for that specific depth, i.e.,

$$K_L = A_1(0.10)^{B_1} = 0.00042(0.10)^{B_2}$$

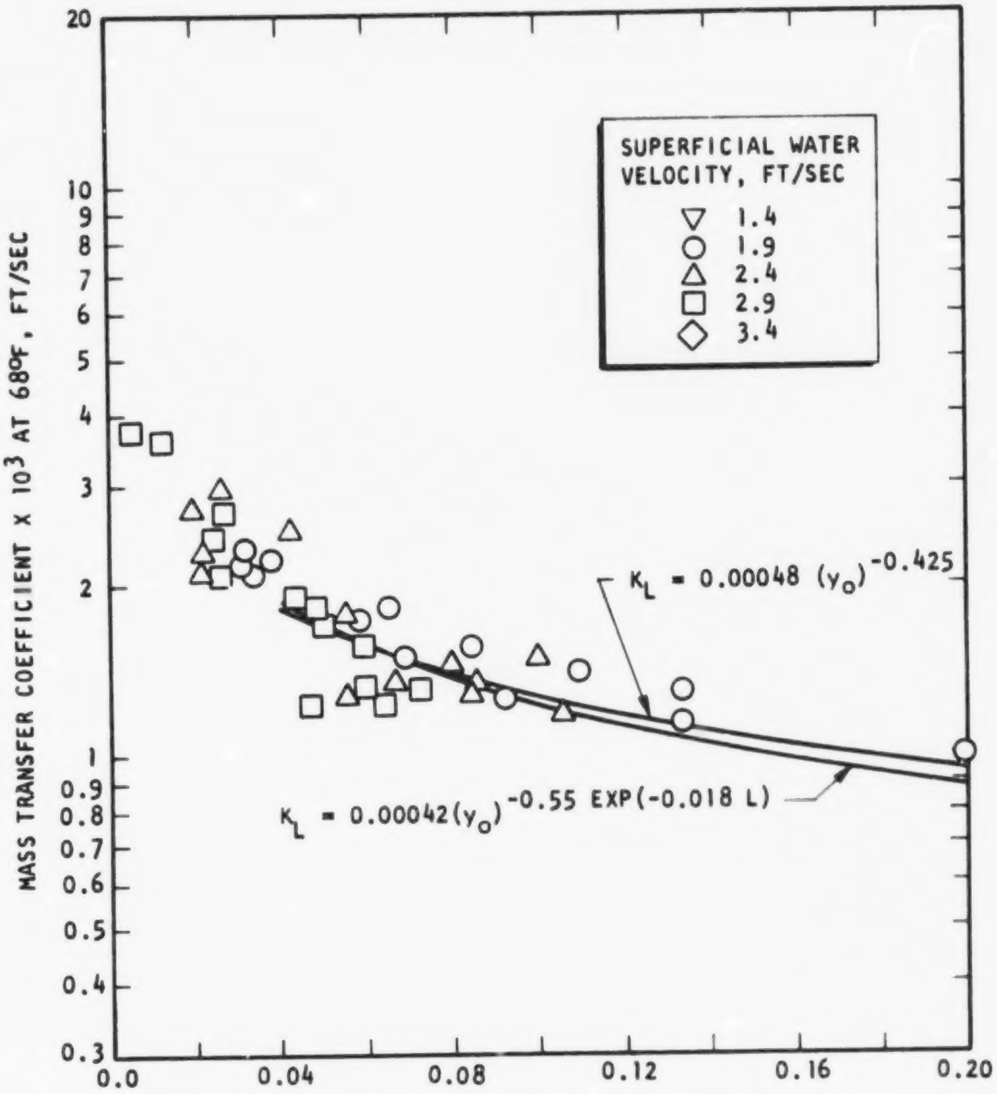


Figure 24. Experimental Mass Transfer Coefficients for 9-ft U-Tube

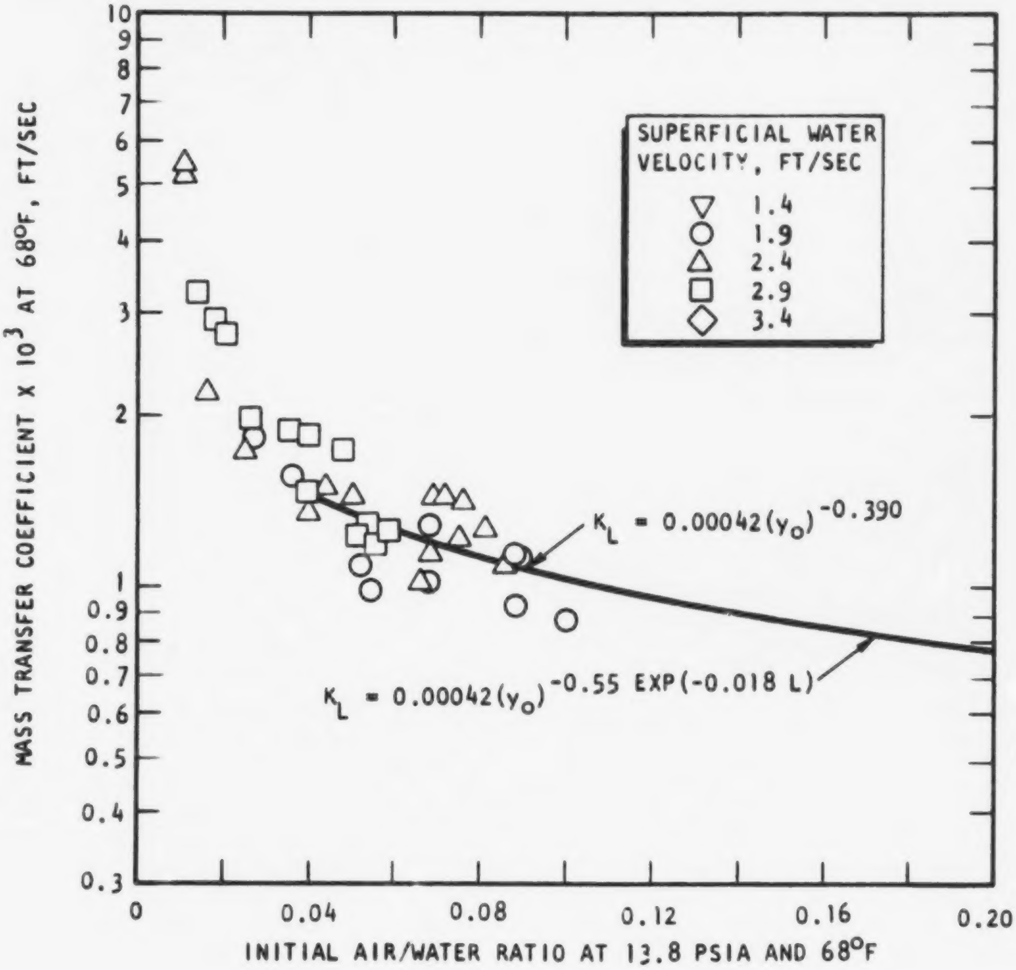


Figure 25. Experimental Mass Transfer Coefficients for 19-ft U-Tube

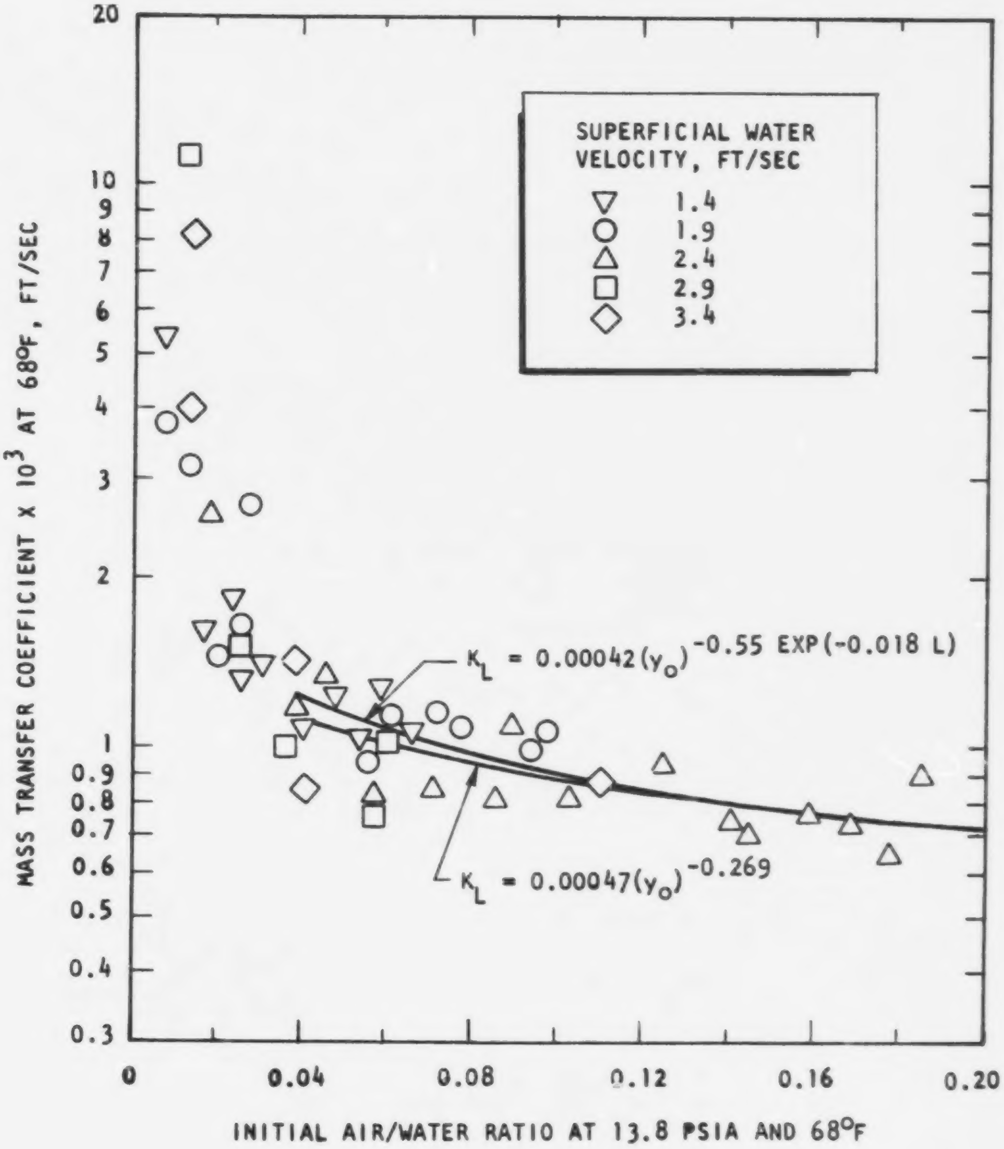


Figure 26. Experimental Mass Transfer Coefficients for 28-ft U-Tube

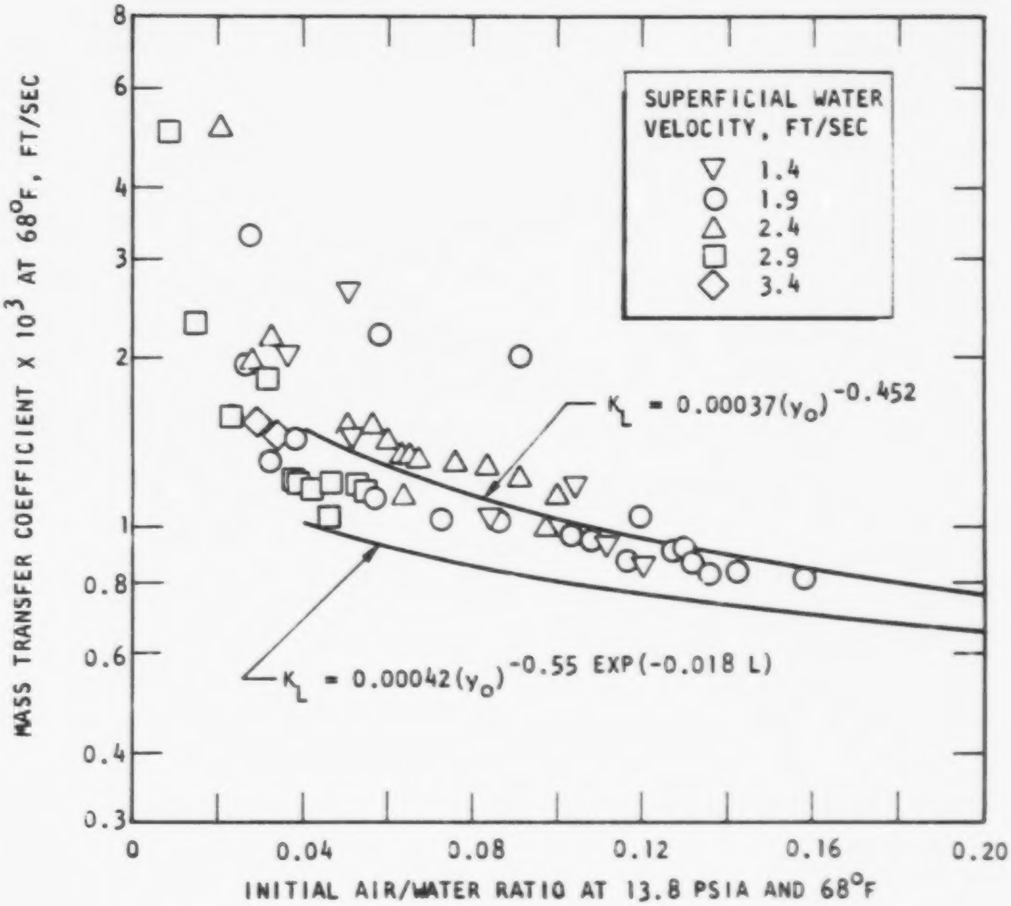


Figure 27. Experimental Mass Transfer Coefficients for 37-ft U-Tube

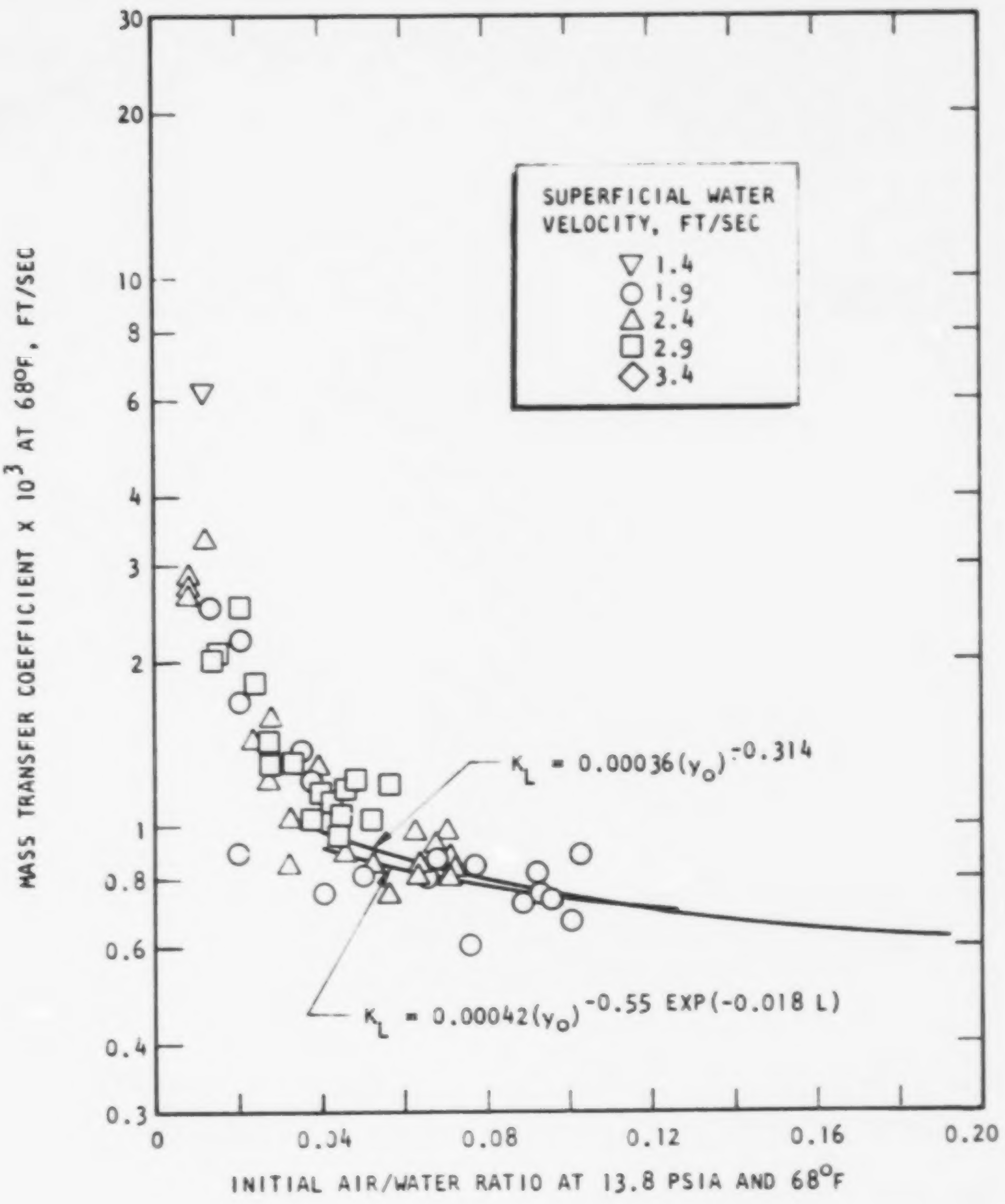


Figure 28. Experimental Mass Transfer Coefficients for 45-ft U-Tube

The resulting values for B_2 as a function of depth are as follows:

Depth	B_2
8'-11"	-0.487
18'-10"	-0.391
27'-11"	-0.316
37'-6"	-0.398
45'-5"	-0.250

It is apparent that B_2 increases systematically with depth except for the 37-ft U-tube. A semi-logarithmic representation of B_2 vs depth gave an excellent linear relationship except for the 37-foot depth. The conclusion was that B_2 could be represented as $B_2 = A_2 \exp(A_3 L)$, where L is depth in ft. The constants A_2 and A_3 were evaluated as -0.55 and -0.018, respectively, giving the final form of the equation for K_L (for y greater than 0.04) as

$$K_L = 0.00042\ (y)^{-0.55} \exp(0.018L) \tag{19}$$

where K_L is the mass transfer coefficient at 68° F in ft/sec, y is the air-to-water ratio at 13.8 psia and 68° F, and L is the U-tube depth in ft. This equation is also plotted in Fig. 24 through Fig. 28. It can be seen that for all depths except 37 ft, the general equation (19) predicts results almost identical to those from the individual equations for each depth. The discrepancy at the 37-ft depth has not been explained. The pressure loss data for this length also deviated from the norm. The agreement with the least squares equation at other lengths strongly suggests that the 37-ft data have some bias.

U-TUBE DESIGN PROGRAM

A computer program was developed to perform design computations for U-tube and similar types of aeration systems. It is almost necessary to use a computer program in making accurate design calculations for such systems because of the need to make finite-difference calculations with reasonably small step-sizes. The design problem becomes partiticularly difficult in cases where the exit pressure is specified but the entrance pressure is unknown; it then becomes necessary to iterate the series of finite-difference calculations in order to converge on a solution which also matches the specified exit pressure. Because of the complexity of the computations, the design bases and system design criteria which were developed during the project were incorporated into a computer program which was then used as the actual design tool.

Configurations and Problem Type Options

Three major configurations or problem types can be analyzed with the program: (1) aspirated-air U-tubes installed in the end of a force main (i.e., full-flowing pipe under pump head), as illustrated by the schematic sketch in Fig. 29; (2) compressed-air U-tubes installed in the end of a force main, as illustrated by the sketch of Fig. 30; and (3) eductors, which are essentially compressed-air U-tubes with the diffuser located at the bottom of the up-leg. The symbols shown for various dimensions in Fig. 29 and Fig. 30 are those used by the program, some of which appear in the output.

Program Outline and Description

The major calculation steps of the design computer program are shown in the flowsheet of Fig. 31. It can be seen that the program repeats most of the calculations iteratively until the convergence criterion for the particular case is satisfied. The usual procedure was to iterate the entrance pressure (p_1) until the calculated exit pressure (p_{12}) matched the specified exit pressure within a given tolerance, for specified values of entrance and exit pipe elevations plus other variables. The convergence techniques had to be somewhat more complex than those used for the data reduction program.

The usual input variables were (for the aspirated-air U-tube option):

geometric information about the venturi aspirator
radii of curvature of bends and elbows
slip velocities and values of X to characterize bubbles
throat pressure (or venturi contraction area ratio)
ambient pressure
water temperature
alpha
inlet D.O. concentration
water flow rate
initial air-to-water ratio
pipe diameters (D_1, D_6, D_9)
system dimensions (A10, A11, A16, A18, A19)

The output variables are illustrated and discussed in a later subsection on program results

Important Relationships and Assumptions (U-tube Design Program)

Most of the equations and relationships developed for the data reduction program (specifically, equations 14-17 and equation set 18) were used as part of the design program. Equation 3 was used to calculate pressure drop across the venturi aspirator. Equation 19 was used to predict oxygen mass transfer coefficients.

Additional developments were made to permit greater generality in predicting mass transfer in the aspirator of an aspirated-air U-tube system. Although equation 8 for venturi mass transfer coefficients was adequate for data reduction, a more general description was required for application to a design program. Specifically, an

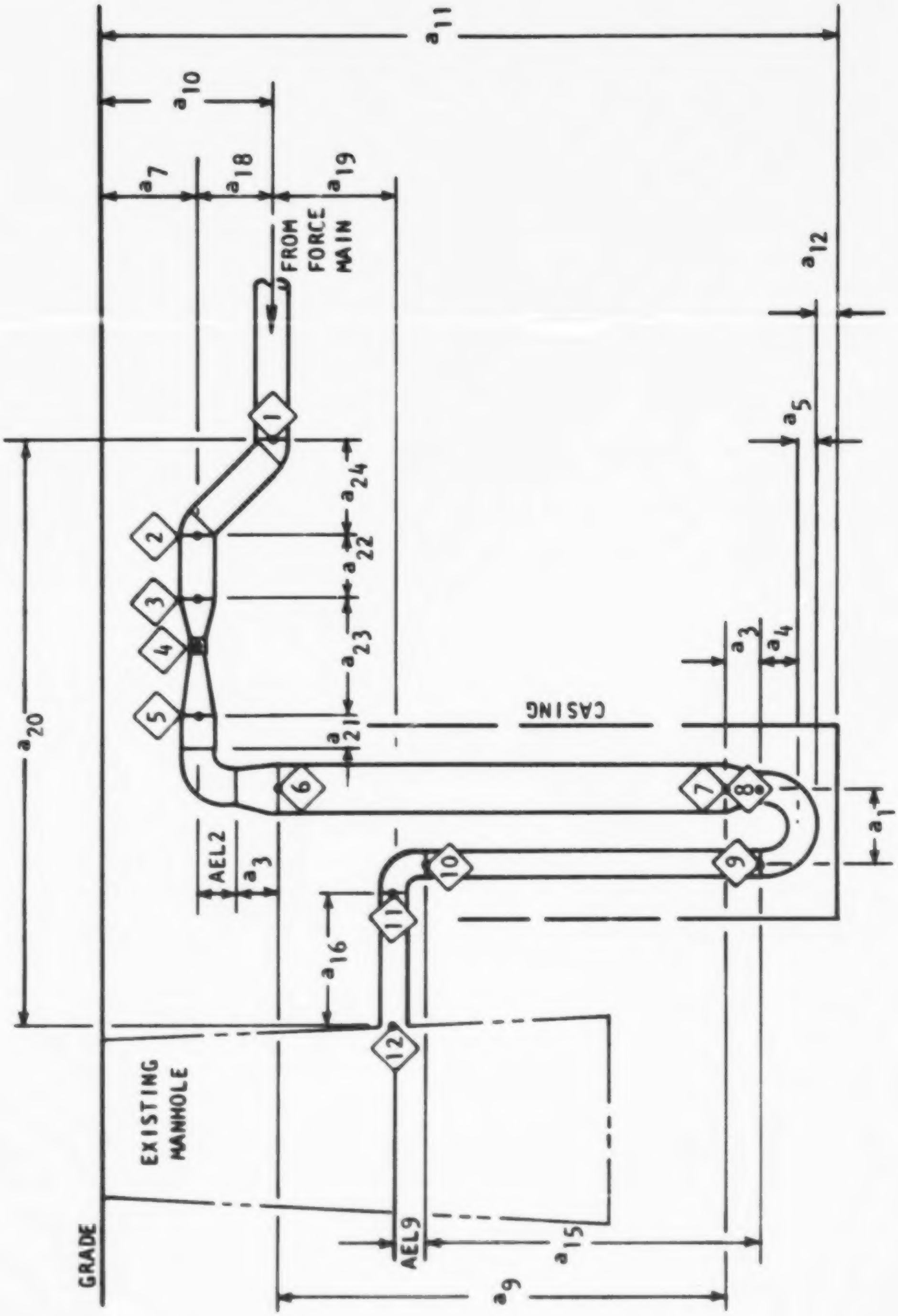

a11
a10
a7
a18
a19
FROM FORCE MAIN
a12
a5
1
2
3
4
5
a24
a22
a23
a21
a20
a3
a4
CASING
6
7
8
9
10
11
12
a1
AEL2
a3
a16
EXISTING MANHOLE
GRADE
AEL9
a15
a9

Figure 29. Schematic Diagram of Aspirated-Air U-Tube

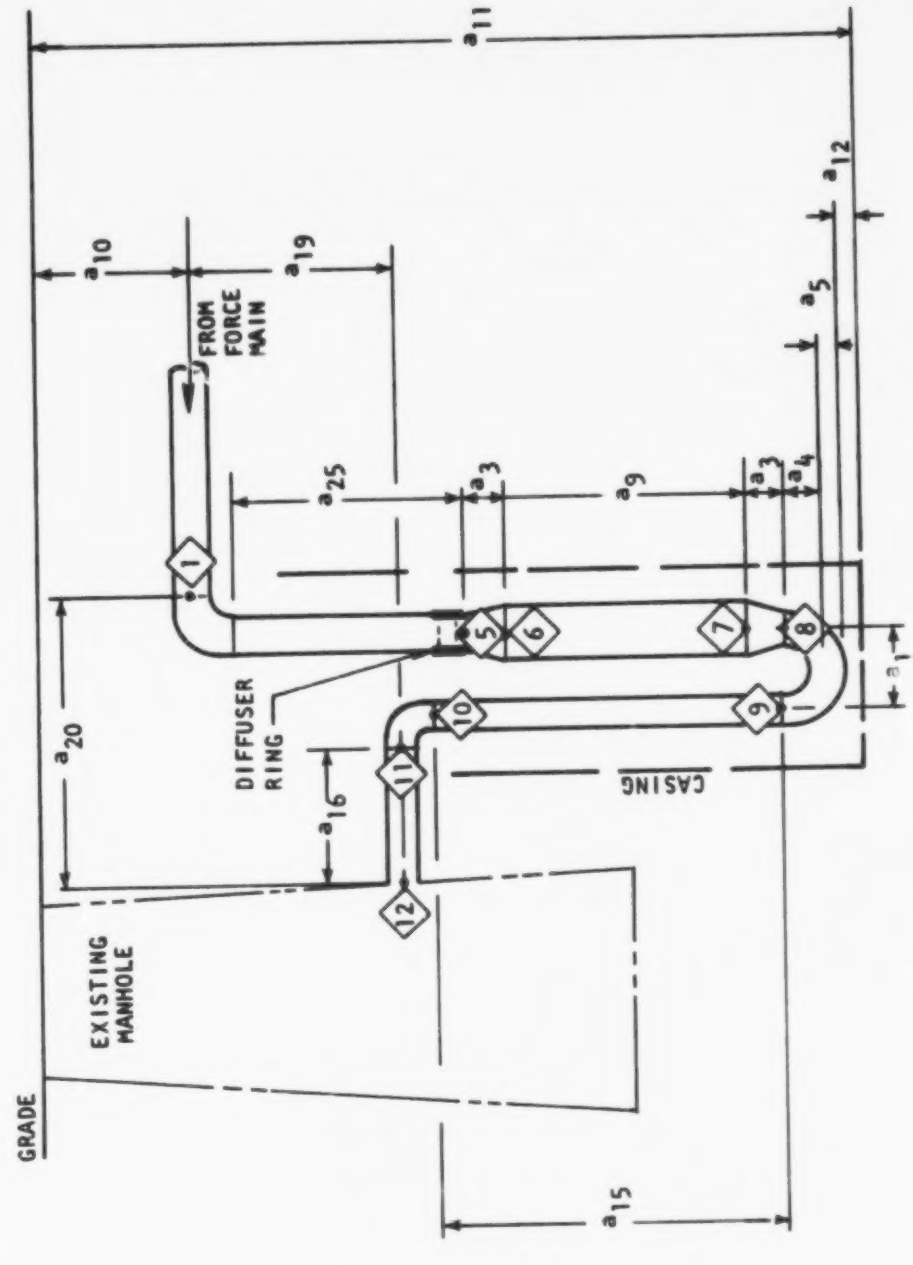

a_{11}
a_{10}
a_{19}
FROM FORCE MAIN
a_{12}
a_5
a_{25}
a_3
a_9
a_3
a_4
1
5
6
7
8
9
10
11
12
DIFFUSER RING
a_{20}
a_{16}
a_1
CASING
EXISTING MANHOLE
GRADE
a_{15}

Figure 30. Schematic Diagram of Compressed-Air U-Tube

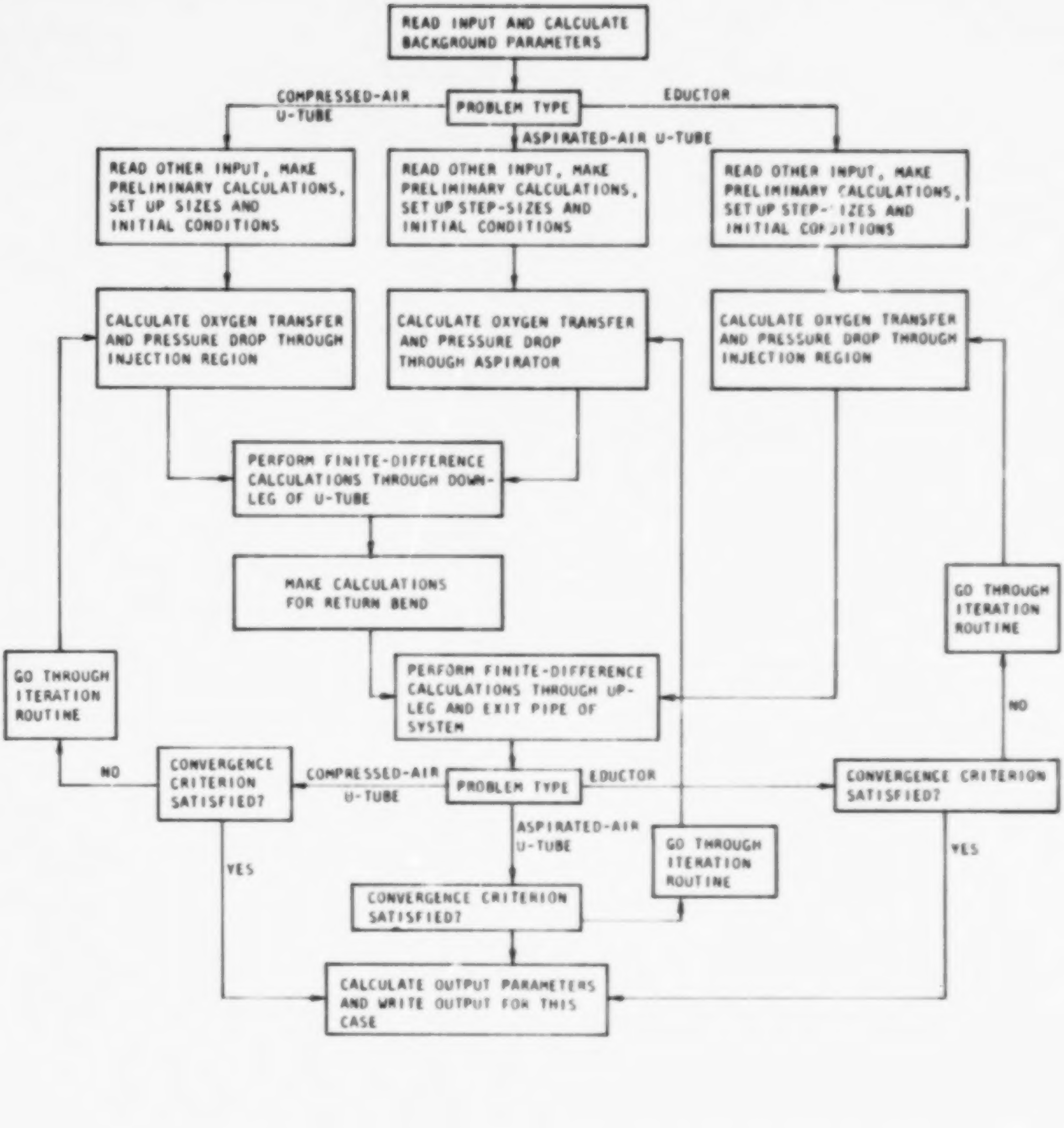

READ INPUT AND CALCULATE BACKGROUND PARAMETERS
PROBLEM TYPE
COMPRESSED-AIR U-TUBE
ASPIRATED-AIR U-TUBE
EDUCTOR
READ OTHER INPUT, MAKE PRELIMINARY CALCULATIONS, SET UP SIZES AND INITIAL CONDITIONS
READ OTHER INPUT, MAKE PRELIMINARY CALCULATIONS, SET UP STEP-SIZES AND INITIAL CONDITIONS
READ OTHER INPUT, MAKE PRELIMINARY CALCULATIONS, SET UP STEP-SIZES AND INITIAL CONDITIONS
CALCULATE OXYGEN TRANSFER AND PRESSURE DROP THROUGH INJECTION REGION
CALCULATE OXYGEN TRANSFER AND PRESSURE DROP THROUGH ASPIRATOR
CALCULATE OXYGEN TRANSFER AND PRESSURE DROP THROUGH INJECTION REGION
PERFORM FINITE-DIFFERENCE CALCULATIONS THROUGH DOWN-LEG OF U-TUBE
MAKE CALCULATIONS FOR RETURN BEND
GO THROUGH ITERATION ROUTINE
GO THROUGH ITERATION ROUTINE
PERFORM FINITE-DIFFERENCE CALCULATIONS THROUGH UP-LEG AND EXIT PIPE OF SYSTEM
NO
NO
CONVERGENCE CRITERION SATISFIED?
COMPRESSED-AIR U-TUBE
PROBLEM TYPE
EDUCTOR
CONVERGENCE CRITERION SATISFIED?
ASPIRATED-AIR U-TUBE
GO THROUGH ITERATION ROUTINE
YES
YES
CONVERGENCE CRITERION SATISFIED?
CALCULATE OUTPUT PARAMETERS AND WRITE OUTPUT FOR THIS CASE

Figure 31. Computation Flowsheet for Design Program

equation was desired which included the effects of throat velocity and throat diameter. The generalized equation was developed on an empirical basis, as described in the following paragraphs.

The work of Jackson and Collins[7] was the only source of applicable experimental data which was found. This study compared the oxygen transfer and energy loss characteristics of two sizes of venturi aspirators. A comparison of the two units, with the range of variables investigated for each, is given below:

Venturi	Entrance Diameter (in.)	Throat Diameter (in.)	Throat Velocities (ft/sec)	Air-to-Water Volume Ratios
Large	3.75	1.25	23, 31, 36, 45	0.163-0.184
Small	0.75	0.25	21, 30, 37, 45	0.141-0.188

Conveniently, the contraction ratios for Jackson's units and the aspirator used in the two-inch U-tube in this project were essentially the same, 9 and 8 respectively. Unfortunately, Jackson's aspirators were horizontally mounted. The assumption that mass transfer is independent of orientation had to be made. Jackson's minimum throat velocities were comparable to the experimental throat velocity at 30 gpm (23.1 fps) for this investigation. Jackson operated only at approximately $y=0.18$ with his lowest throat velocities. At 30 gpm the maximum air-to-water ratio attained was 0.057 for this investigation. Extrapolations had to be made to find a common basis of comparison with respect to air-to-water ratio.

A linear extrapolation of the 30 gpm curve (Fig. 17) to $y=0.18$ gave K_La equal to 11,400 hr^{-1}. This value is plotted with Jackson's mass transfer coefficients as a function of throat diameter in Fig. 32. Evaluation of the slope shows that, at $y=0.18$, K_La is approximately proportional to throat diameter raised to the -1.35 power. A plot of K_La vs throat velocity (with y approximately equal to 0.18) is shown in Fig. 33. The slopes for Jackson's two horizontal aspirators are 1.40 and 1.30; the slope for the vertical venturi tested in this project is 2.72. It should be noted that Jackson's lowest throat velocity is roughly equal to the largest for this investigation. The discrepancy in the slopes (i.e., a different throat velocity functionality) is probably due to the different orientation of the aspirators or the difference in throat velocity range. Since Jackson's data are for horizontal aspirators (the most likely orientation for large-scale facilities), these data were used as a basis for determining the throat velocity dependence. Therefore, K_La was concluded to be proportional to the 1.35 (mean of 1.30 and 1.40) power of throat velocity. Based on the linear air-to-water dependence shown in Fig. 17, the general form for the venturi mass transfer coefficient is

$$K_La = 576\ y \left(\frac{u_4}{D_4}\right)^{1.35} \qquad (20)$$

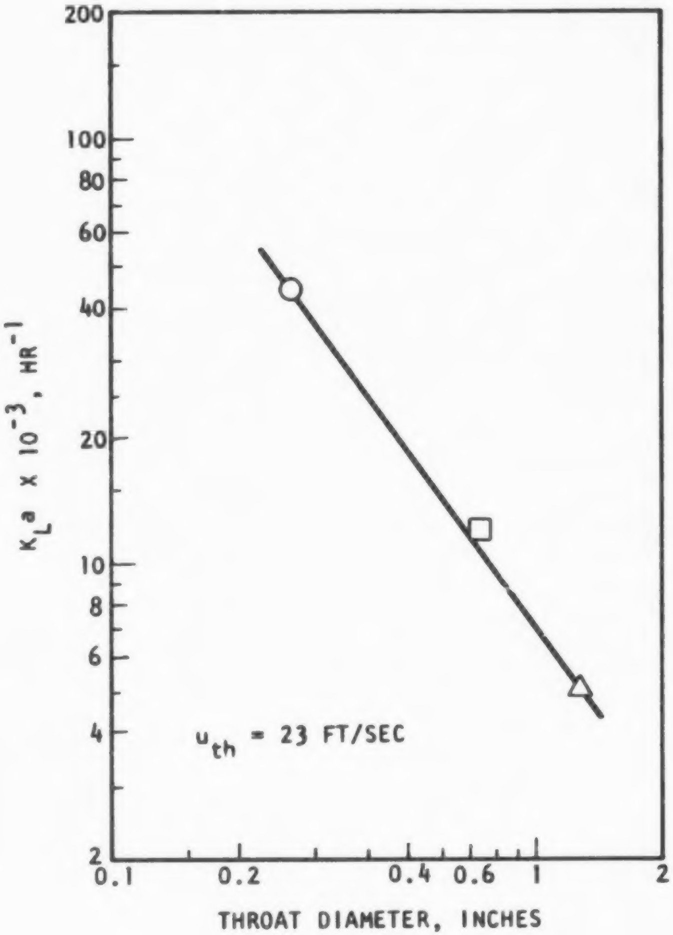


Figure 32. Effect of Venturi Throat Diameter on Mass Transfer Coefficient

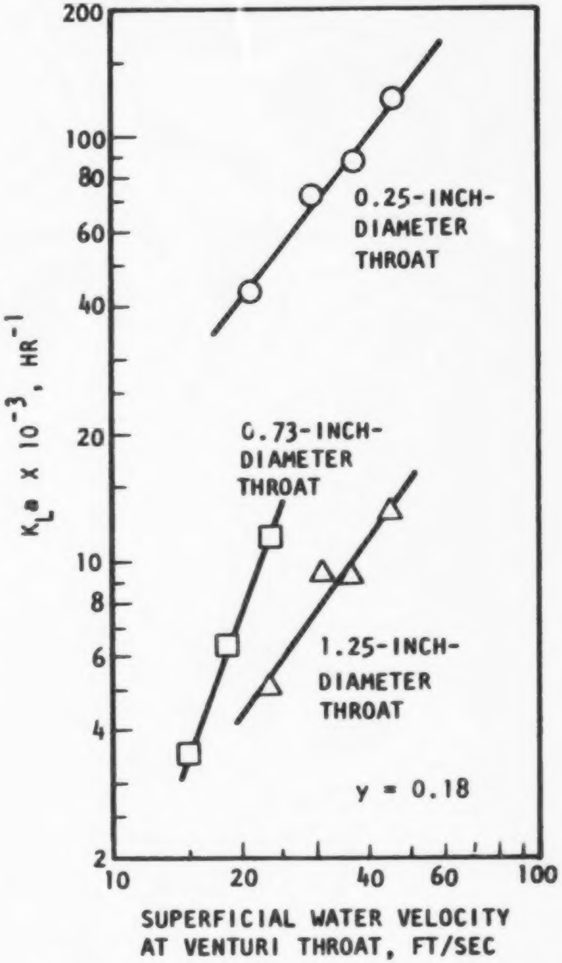


Figure 33. Effect of Venturi Throat Water Velocity on Mass Transfer Coefficient

where K_La is the mass transfer coefficient at 68° F in hr^{-1}, u_4 is the throat velocity in ft/sec, D_4 is the throat diameter in inches, and y_o° is the initial air-to-water volume fraction at 1 atm and 68° F.

Equations 6 and 20 can be combined, with some rearrangement, to give

$$\frac{C_5 - C_3}{C_s - C_3} = 1 - \exp\left[\frac{-29.4\, y_o^\circ\, u_3^{0.35} E^{2.025}\, V}{D_3^{3.35}}\right] \qquad (21)$$

in which the venturi entrance velocity, u_3, is in ft/sec; the venturi diffuser volume, V, is in ft^3; and the venturi entrance pipe diameter, D_3, is expressed in inches. For the more specific case of a venturi with a conical diffuser (of half-angle b), equation 21 becomes

$$\frac{C_5 - C_3}{C_s - C_3} = 1 - \exp\left[\frac{-0.00222\, y_o^\circ}{\mathrm{Tan}(b)} \left(\frac{u_3}{D_3}\right)^{0.35} E^{2.025}(1-E^{-1/2})(1+E^{-1/2}+E^{-1})\right] \qquad (22)$$

Equation 22 predicts that the amount of oxygen transfer in a venturi aspirator will increase as y_o°, u_3, or E increase, and will decrease as b or D_3 increase. The values of b and E have a strong effect on the oxygen transfer (primarily as they affect residence time in the diffuser). The air-to-water fraction also has a strong effect on the transfer, as should be expected. Neither the entrance velocity nor the entrance pipe diameter is predicted to have a very pronounced effect on the oxygen transfer. Representative parametric values for oxygen transfer in a venturi aspirator (with b = 7.5 degrees), as predicted by equation 22, are given below.

y_o°	u_3 (ft/sec)	D_3 (inch)	E	$\frac{C_5 - C_3}{C_s - C_3}$
0.05	2	2	4	0.0122
0.05	4	12	4	0.0083
0.10	2	2	4	0.0242
0.10	2	12	4	0.0130
0.10	2	24	4	0.0102
0.10	4	2	4	0.0307
0.10	4	12	2	0.0030
0.10	4	12	4	0.0165
0.10	4	12	6	0.040
0.10	4	12	8	0.071
0.10	4	12	10	0.111
0.10	4	12	12	0.158
0.10	4	24	4	0.0130
0.10	6	2	4	0.0353
0.10	6	12	4	0.0190
0.10	6	24	4	0.0150
0.10	8	2	4	0.0390

y_o^o	u_3 (ft/sec)	D_3 (inch)	E	$\frac{C_5 - C_3}{C_s - C_3}$
0.10	8	24	4	0.0165
0.15	2	2	4	0.0360
0.15	4	12	4	0.0247
0.20	2	2	4	0.048
0.20	4	12	4	0.033
0.25	2	2	4	0.059
0.25	4	12	4	0.041

Potential users of equation 22 should keep in mind that it was developed from a limited set of data (the experimental data obtained during this project plus all applicable data which could be found in the literature). These data were for three venturi aspirators, with entrance pipe nominal diameters of 3/4, 2, and 4 in. The diffusers were conical in each case, with full-cone angles of about 7 degrees. The nozzle contraction area ratios were 8 and 9. Equation 22 was developed to permit design predictions, since no other design basis was available, and it should give reasonable estimates of venturi aspirator oxygen transfer for aspirators which are geometrically similar to the three for which experimental data exist. Equation 22 should also give reasonable predictions for substantially larger aspirators than these three, since the effect of diameter appears to be modest, as long as the aspirators have similar configurations.

However, for large scale applications the length and cost of a conical diffuser with a small divergence angle would become excessive, and other diffuser designs would probably be used: perhaps a cone with larger divergence angle, or with a contoured divergence section (e.g., the aspirators designed for the Jefferson Parish applications, as described in the next major section). Alternatively, in large scale applications, the aspirator might be a "trough", i.e., have venturi contours in only one plane, with a rectangular flow cross-section at any station. It would be fortuitous if equation 22 gave accurate predictions for such geometrically different types of venturi aspirators, or for a wide range of contraction area ratios differing from the 8 to 9 range represented by the experimental data. Additional data are needed to permit development of a more general relationship for predicting venturi oxygen transfer.

Output from Design Program

A number of print-outs from the design program are reproduced and explained in Appendix D. Typical parametric design trands and the application of the program to system design are illustrated in the following section on design of aeration systems for the Jefferson Parish, Louisiana sewer system.

JEFFERSON PARISH DESIGNS

Design and optimization studies of various types of aeration systems for in-situ aeration in sanitary sewer lines were conducted in support of the FWPCA Research and Development Grant (11010 ELP) to Jefferson Parish, Louisiana. The following sections describe the application site and some of its special characteristics, design objectives and constraints, the optimization studies conducted, and the final designs developed for use in this FWPCA grant project.

DESCRIPTION OF APPLICATION SITES

Jefferson Parish is adjacent to the west side of Orleans Parish in which most of the city of New Orleans lies. The portion of Jefferson Parish in which the aeration systems are to be installed in bounded by Lake Pontchartrain on the north and the Mississippi River on the south. More specifically, the sewer lines under study collect waste water from part of the area north of Air Line Highway and flow northward to the Helois Treatment Plant. This area is quite level and much of it is below the elevation of Lake Pontchartrain and the Mississippi River at this point. The difficulties of sewer construction caused by the high ground water level and low rigidity of the soil have necessitated the use of minimum slopes on gravity sewer lines plus numerous pumping stations. The net waste water velocities are small compared with those in many areas, and there have been some septicity problems in the sewers. It is, of course, important to prevent septic (anaerobic) conditions from developing in a sewer line because of the resultant odor, corrosion, and subsequent treatment plant problems which this can cause. The Jefferson Parish Department of Sanitation has been active in improving its sewer systems to eliminate many of the potential trouble spots, primarily by installing additional lift stations and more force mains to decrease the average sewage residence times. This project had the objective of investigating aeration as a method for septicity control.

After a considerable study by various parties concerned with the project, a number of alternative sites for aeration systems were selected. These included: three for aspirated-air U-tubes (Stations 5, 7, and 30); one for a compressed-air U-tube (Station 9) and one for a horizontal in-line venturi aspirator (Station 31). Table 4 lists the principal bases for design of these five aeration systems. At the time of this writing, bids for construction have been received. Final selection of aeration stations to be constructed will be made by Jefferson Parish after evaluation of bids for various aeration designs.

TABLE 4

DESIGN BASES FOR FIVE AERATION SYSTEMS

Station	5	7	30	9	10
Type of Aerator	aspirated-air U-tube	aspirated-air U-tube	aspirated-air U-tube	compressed-air U-tube	in-line venturi aspirator
Location	end of P.S. H56 discharge F.M.	end of P.S. H53 discharge F.M.	end of P.S. H52 discharge F.M.	end of P.S. H43 discharge F.M.	several hundred feet upstream of Sta. 30
Incoming line size (in)	12	10	8	8	8
Base design flow rate (gpm)	1800	670	1000	300	1000
Distance from grade to entrance line invert (ft)	4.0	5.5	9.0	4.7	4
Distance from grade to exit manhole bottom (ft)	11.2	9.1	20.0	4.7	-
Inlet D.O. concentration (mg/l)	0.2	0.2	0.2	0.2	0.2

DESIGN OBJECTIVES AND CONSTRAINTS

The primary objective of each aeration facility was to efficiently dissolve as much oxygen in the waste water stream as possible within the particular constraints of each chosen site.

A very important consideration which imposed constraints on the designs was that they should not offer any opportunity for plugging. Most of the specifications for lift pumps in this area require passage of a "3-inch diameter sphere" (in a few cases 4-inch diameter is specified). Consequently, in the U-tube designs no cross-section with a dimension less than four inches was permitted. This imposed a constraint on the minimum flow rate for which an aspirated-air U-tube could be applied. With pressure drops typical of those for the Jefferson Parish designs, the flow rate must be greater than about 300 gpm to keep the required aspirator throat diameter at least 4 inches.

Another possible source of plugging could be the return bend at the bottom of the U-tube. A concentric configuration would have several construction advantages; however, it could produce two possibilities of plugging in this application: the annular space between the inner and outer pipes would be less than 4 inches for these applications, and the abrupt edge at the bottom of the inner pipe could possibly result in some hang-up of material. Consequently, all designs used a literal U-bend between separate down and up pipes, as shown in Fig. 29. It was necessary to ensure that all solid material would be carried up the up-leg and transported from the U-tube system. Although an up-leg velocity of approximately 2 ft/sec would be sufficient to transport sand and prevent silting (as discussed in a previous section), this might not be high enough to transport larger items which could still be passed by the pumps. The Parish design rules for lift pump vertical risers require the velocity to be at least 4 ft/sec. This lower limit on up-leg velocity was also used in these designs.

One major constraint was shared by all four of the aspirated-air systems: the throat pressure must be less than the ambient pressure in order to aspirate air into the flowing water stream. This is not particularly difficult in a gravity-flow system where the pressure at the entrance to the aspirator is merely due to the height of liquid above it. In a force-main application, however, the design is more difficult because the aspirated entrance pressure can be considerably greater than the ambient pressure. If the pressure drop downstream of the aspirator ($p_3 - p_{12}$ using the station numbers previously shown in Figures 1 and 29) is substantial, the aspirator contraction ratio must be much larger (throat smaller) than for a corresponding gravity flow application. This, in turn, leads to a higher ratio of permanent pressure drop to throat pressure decrease, R, since R increases with increasing venturi contraction area ratio. This is not an overpowering design consideration; however, it does impose more restrictive constraints (and generally results in higher overall head losses) on a design for a force main than for a gravity flow situation.

Another set of design considerations centered around the existing system and pump characteristics. Many of the existing lift pumps were operating below their design lifts, and most could also be uprated with larger impellers without changing motors. There was, however, considerable variation in the characteristics at the five sites, and this was considered in the designs.

An alpha value of 0.8 (ratio of oxygen mass transfer coefficient in waste water of interest to coefficient for "tap water") was used in all the calculations for Jefferson Parish aeration systems. This is the value customarily used by the FWPCA Taft Water Research Center,[14] and very similar to the value of 0.82 given in Ref. 15 for fresh raw domestic sewage. If the sewage had no remaining dissolved oxygen and a high initial oxygen demand, the measured oxygen transfer would be less than predicted with the 0.8 alpha factor. The actual amount of oxygen uptake, in such a case, may be even greater than the change in D.O. predicted with an alpha of 0.8; however, the final D.O. level would be smaller than the predicted value because of the high initial oxygen demand. The lower alpha values reported in the literature for various samples of raw sewage may include this effect.

OPTIMIZATION STUDIES AND FINAL DESIGNS FOR ASPIRATED-AIR U-TUBES

A number of configurations for these aerators were considered in the process of choosing the final configuration sketched in Fig. 29, which appeared in the previous section. A large number of parametric computations were made for different configurations and design conditions using the design computer program previously described. It was soon found that it is very important to keep the elevation of the aspirator as high as possible and the elevation of the exit line to the manhole as low as possible. Both of these conditions help minimize the required aspirator contraction area ratio, with attendant improvement in system pressure drop characteristics. Having the aspirator as high as possible also is of value in reducing or, in some cases, preventing the upstream forced main from partially draining during pump off-cycles. Excessive drainage would have undesirable effects on start-up of the aspirator system each time the pump was operating.

Other parametric calculations led to the conclusion that the velocities in all parts of the aspirated-air U-tube system should be as low as possible within the design constraints. This meant, in this particular application, that the up-leg velocities should be greater than ¼ ft/sec but as near to ¼ ft/sec as actual pipe sizes would permit. This conclusion also meant that the down-leg velocities should be approximately 1.5 to 2.0 ft/sec, in order to keep them as small as possible while still maintaining proper air bubble entrainment. It was found that the added expense of pipe reducers to permit a larger down-leg pipe size was definitely justified by the increase in oxygen transfer which results from the longer residence time.

Some of the more typical parametric design trends are illustrated in Fig. 34 through Fig. 41, in which each curve represents a series of cases. Fig. 34 displays three important design variables for designs at Station 5 (exit dissolved oxygen concentration, overall pressure drop across the aeration system, and the required aspirator contraction area ratio, defined as the entrance pipe cross-sectional area divided by the throat cross-sectional area). Curves for each of these three variables are shown as a function of the amount of oxygen supplied (i.e., the amount of oxygen in the air which is aspirated into the flowing water stream), and for four casing depths (note that the actual U-tube depth is typically 4 to 9 ft less than the casing depth, which is measured from grade to the bottom of the casing). The corresponding sets of parametric design curves for stations 7 and 30 are similar to Fig. 34. It can be seen that some air can be aspirated even without a reduced diameter throat section. As the desired amount of oxygen to be supplied (or exit D.O. concentration) is increased, it becomes necessary to constrict the throat cross-section to a greater extent. This results in an increase in exit D.O. concentration, but also produces an excessive overall head loss. The rapid increase in head loss for small throat cross-sectional areas is a result of the "magnification effect" previously discussed, which is characteristic of and an inevitable consequence of a force main application.

In order to more clearly illustrate the trade-offs between exit D.O. concentration and overall head loss, the parametric results of Fig. 34 and analogous results for stations 7 and 30 have been cross-plotted in Fig. 35 through Fig. 37, in which the amount of oxygen supplied is an implicit parameter. It is coincidental, rather than theoretical, that the curves of required aspirator contraction area ratio for the various casing depths are essentially identical. In these three figures, it can be observed that the cost in head loss for incremental increases in exit D.O. concentration becomes relatively greater as the exit D.O. levels approach saturation.

The effect of casing depth on parametric designs is illustrated for station 5 in Fig. 38. The effects of other variables on fixed aspirator designs are shown parametrically in Fig. 39 and 40. Among other observations which can be made from these results, it is found that the decrease in exit D.O. concentration with increasing water flow rate is somewhat less rapid than the increase in head loss. However, these curves again illustrate the importance of keeping the water velocities as low as possible within the design constraints. Many other parametric design studies were and could be made; however, these results illustrate many of the major trends.

After generating parametric design data, as typified in the previous paragraphs, the pump characteristics (for the pump upstream of each station) were matched with the flow characteristics of the force main plus the U-tube system to be added. Fig. 41 illustrates this procedure. Point A, representing the original operating point before any

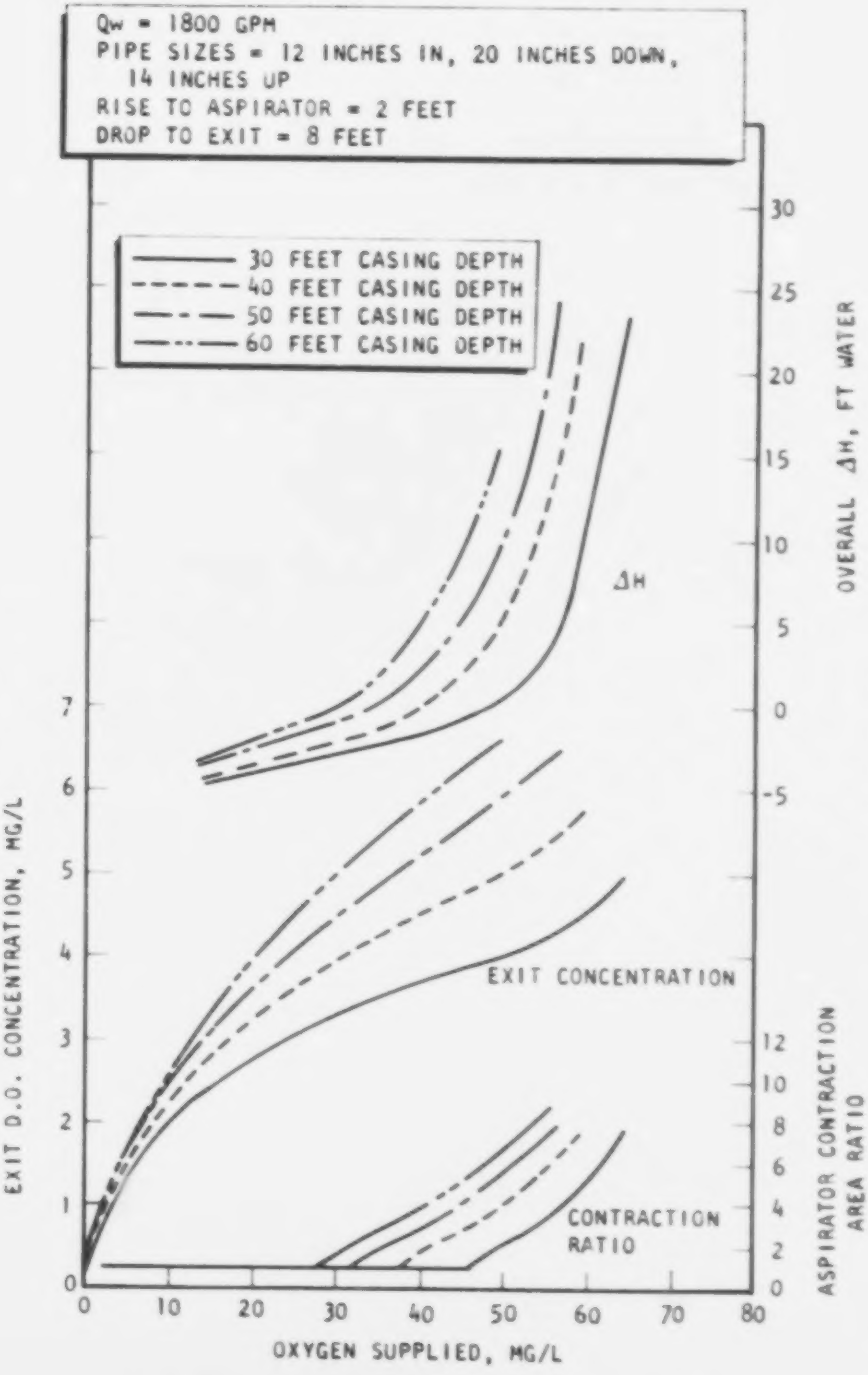


Figure 34. Aspirated-Air U-Tube Parametric Designs for Station 5

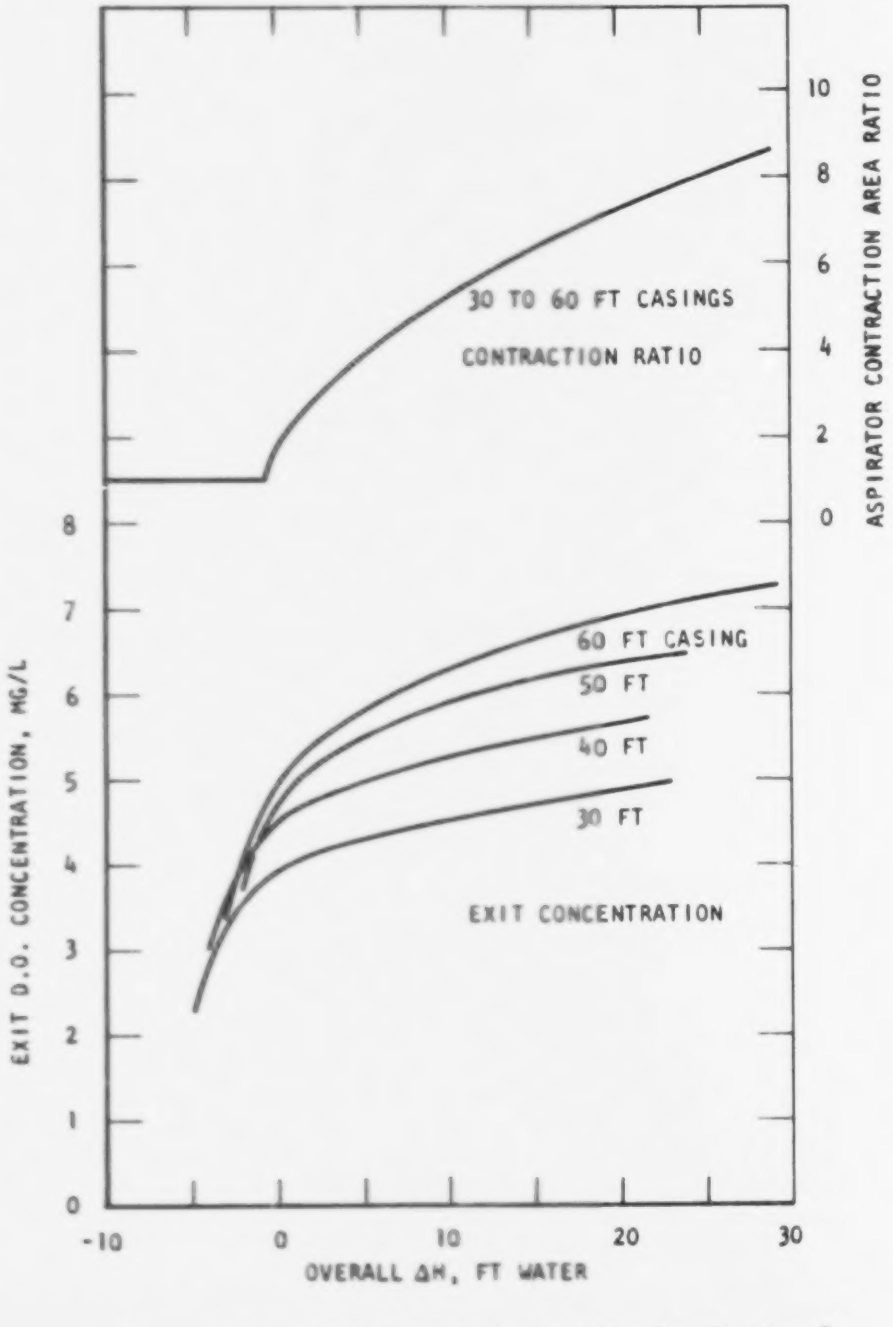


Figure 35. U-Tube Design Trade-Offs for Station 5

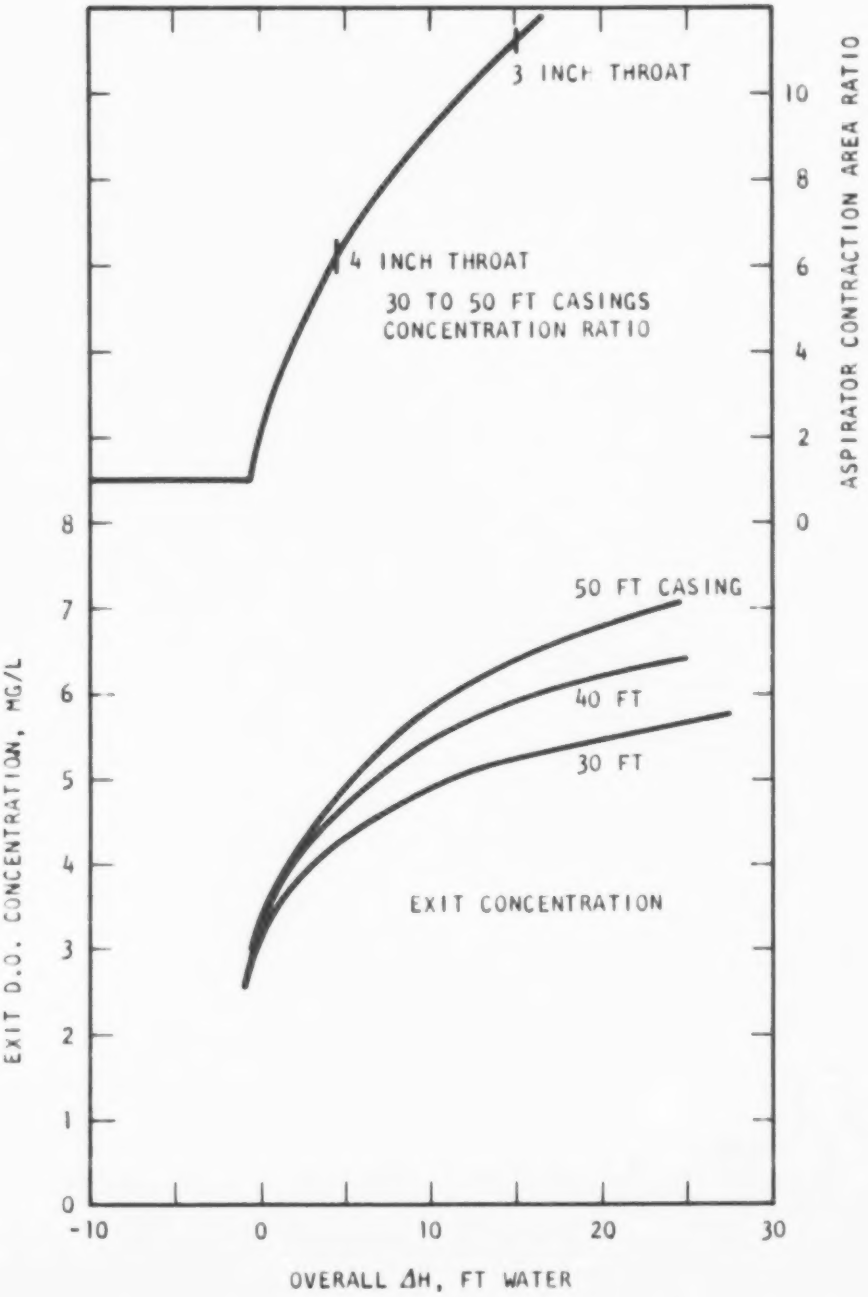


Figure 36. U-Tube Design Trade-Offs for Station 7

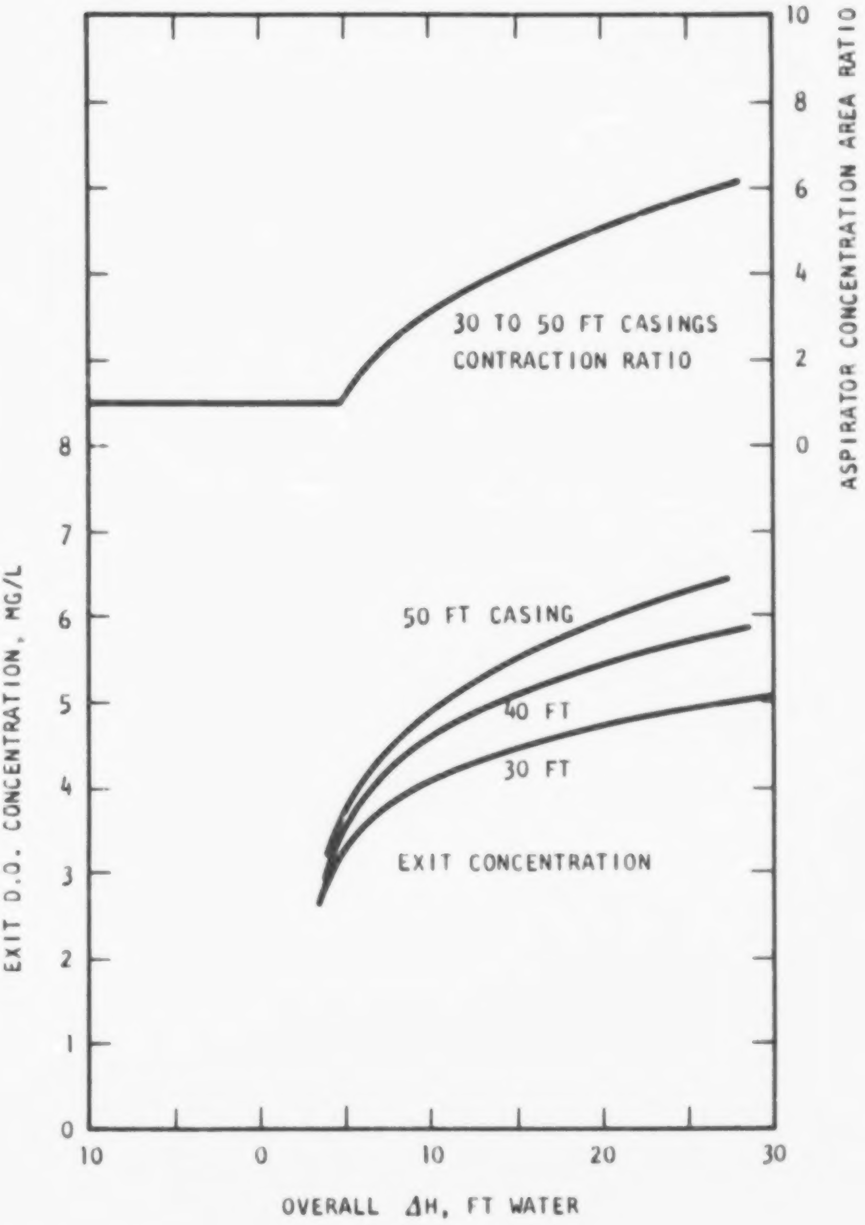


Figure 37. U-Tube Design Trade-Offs for Station 30

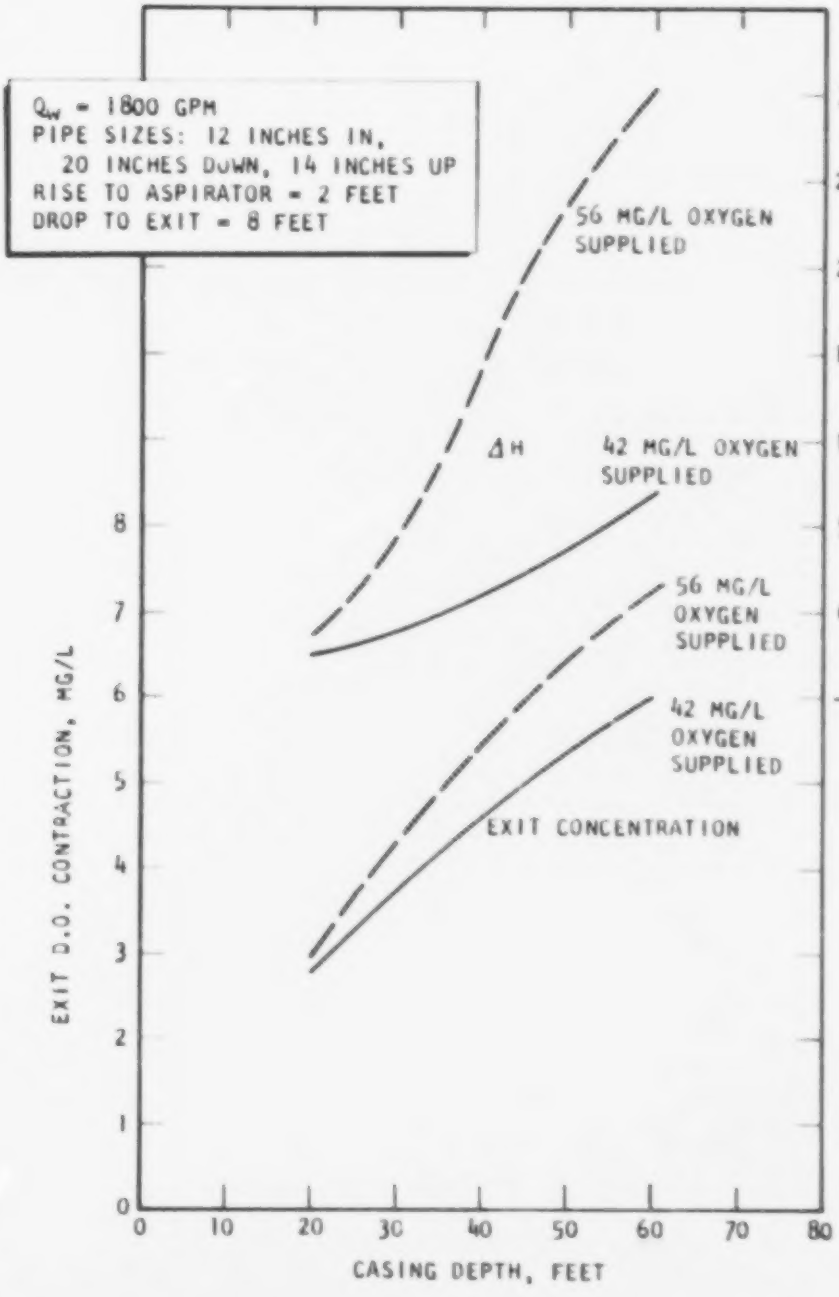


Figure 38. Effect of Casing Depth on U-Tube Designs for Station 5

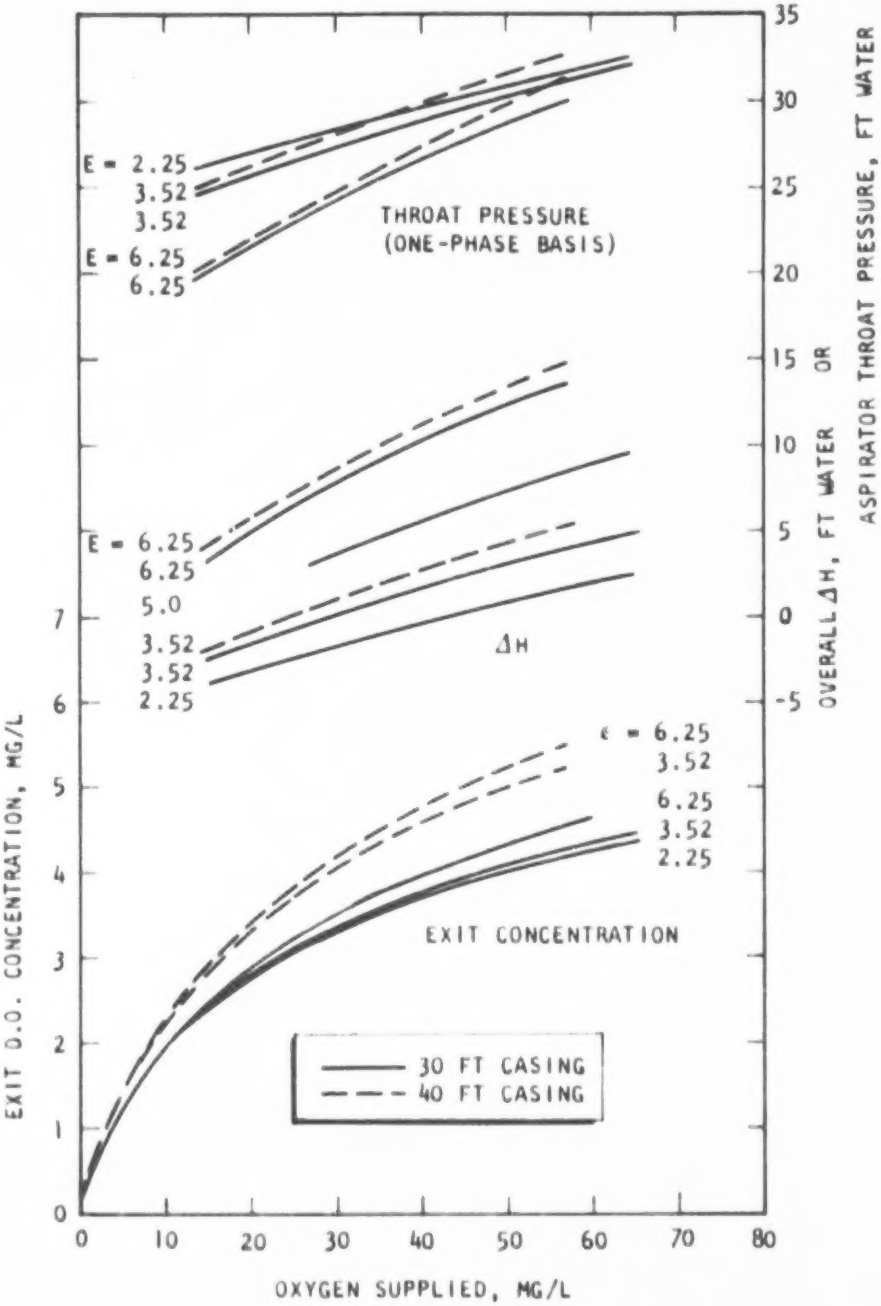


Figure 39. Parametric Performance for Fixed Aspirator Contraction Area Ratios at Station 5

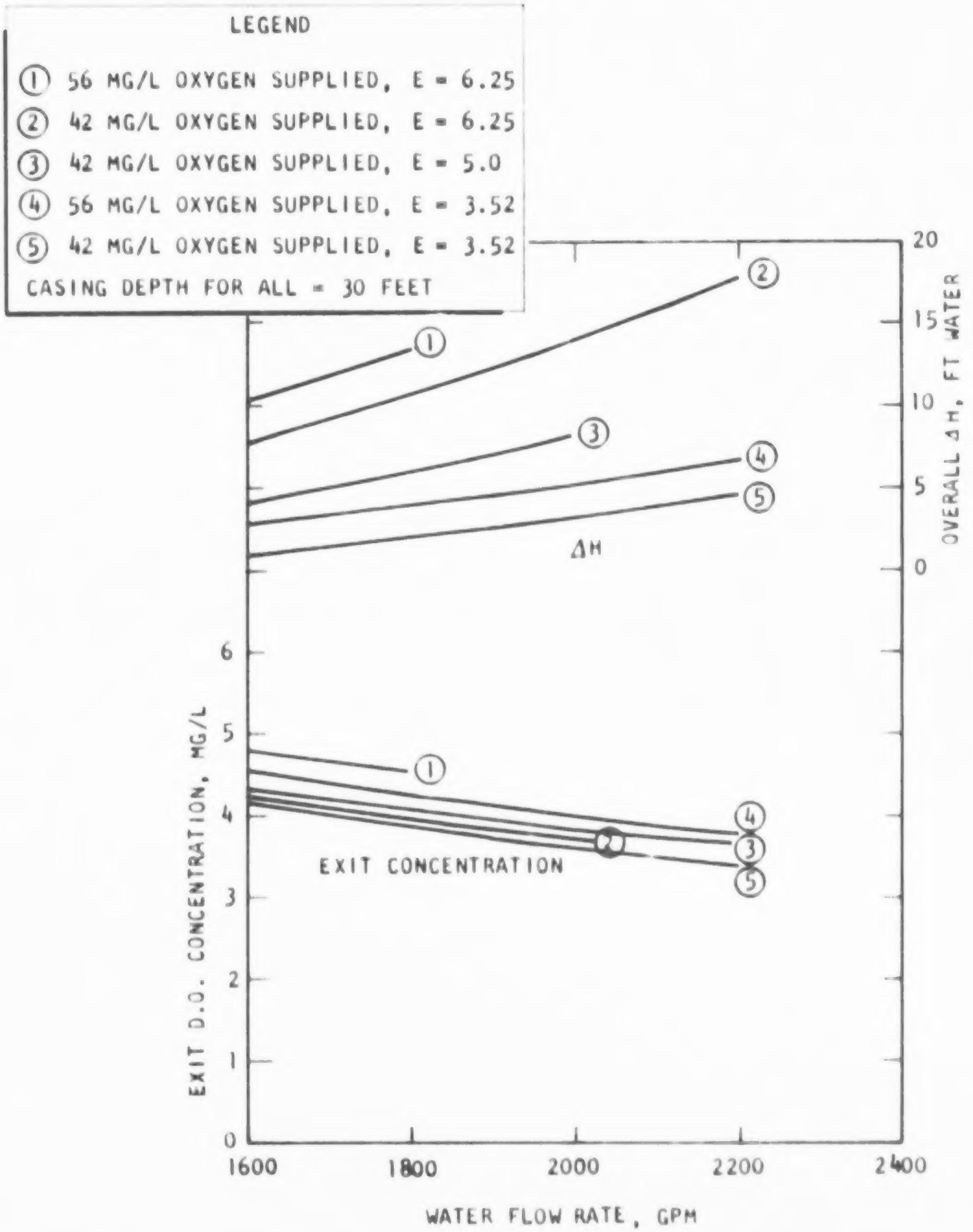


Figure 40. Effect of Water Flow Rate on Fixed Aspirator Designs for Station 7

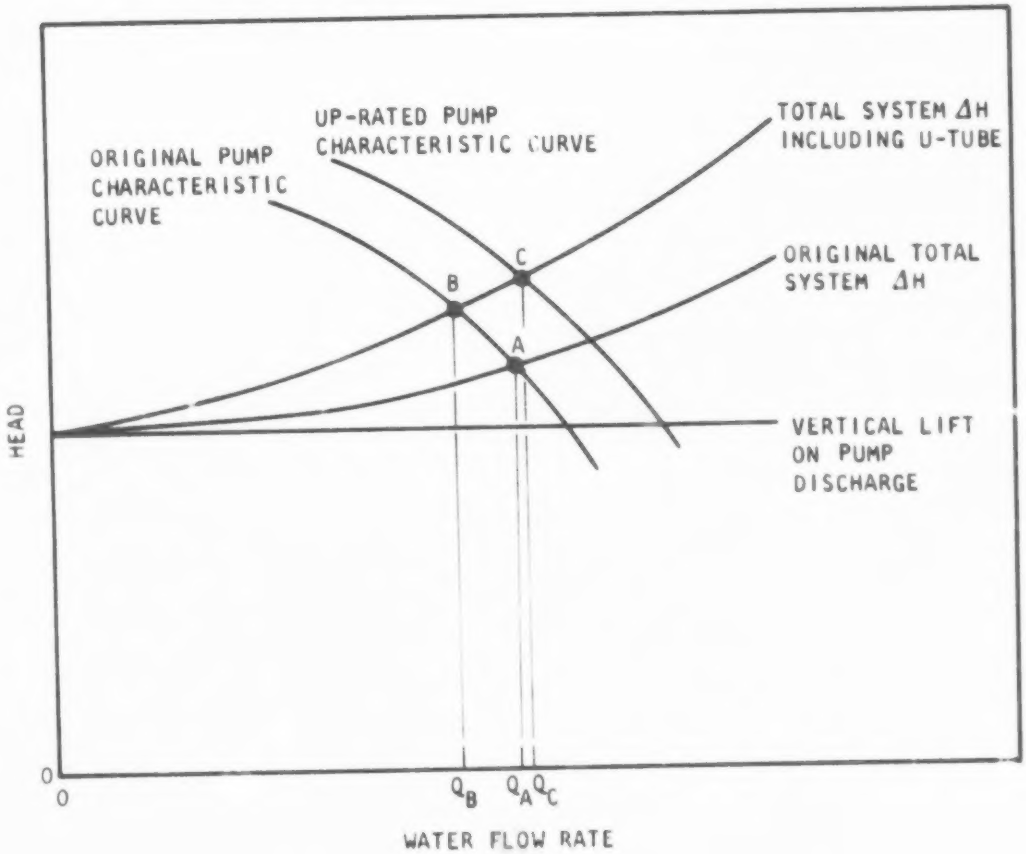

UP-RATED PUMP
CHARACTERISTIC CURVE
ORIGINAL PUMP
CHARACTERISTIC
CURVE
TOTAL SYSTEM ΔH
INCLUDING U-TUBE
ORIGINAL TOTAL
SYSTEM ΔH
C
B
A
HEAD
VERTICAL LIFT
ON PUMP
DISCHARGE
0
0
Q_B
Q_A
Q_C
WATER FLOW RATE

Figure 41. Diagram Illustrating Matching of System and Pump Characteristics

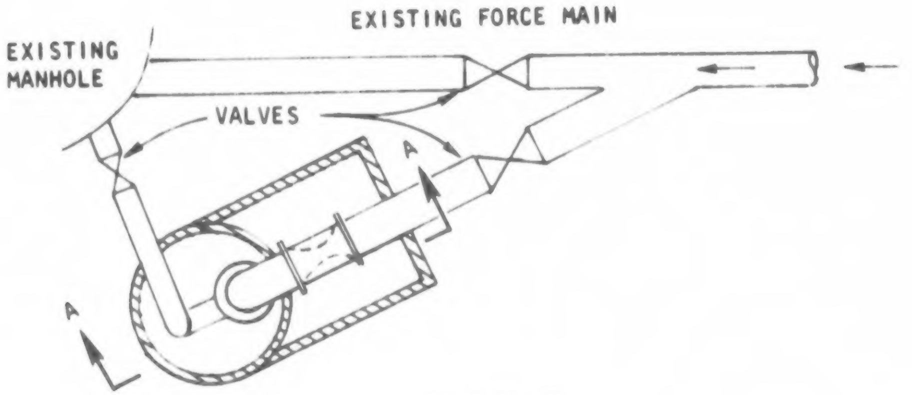
changes to the sewer system, is located at the intersection of the pump characteristic curve and the original total system head curve. Point B is the new operating point after installation of a U-tube system (there could be many U-tube characteristic curves drawn and, consequently, many different point B's, but an efficient U-tube design was chosen in each case). If the new flow rate, Q_B, was lower than desired, then pump modifications were considered. In most cases, the existing pump and motor could accept a larger impeller without other changes. The pump characteristic curve with a larger impeller is represented by the "up-rated pump characteristic curve" in Fig. 41, and point C is the resulting operating point after installation of a U-tube system.

The final designs for the three aspirated-air U-tube systems at Stations 5, 7, and 30 are shown in Table 5 and Fig. 42. These specify all the important design parameters which influence the system operation. Careful consideration was also given to aspirator design and instrumentation for the purposes of obtaining good information about the operating characteristics. Such instrumentation would not be required in a strictly operational aeration system, but was most important for these initial development systems. The designs given by Table 5, Fig. 42, and details of instrumentation and aspirators were used by the consulting engineering firm to prepare detailed construction drawings.

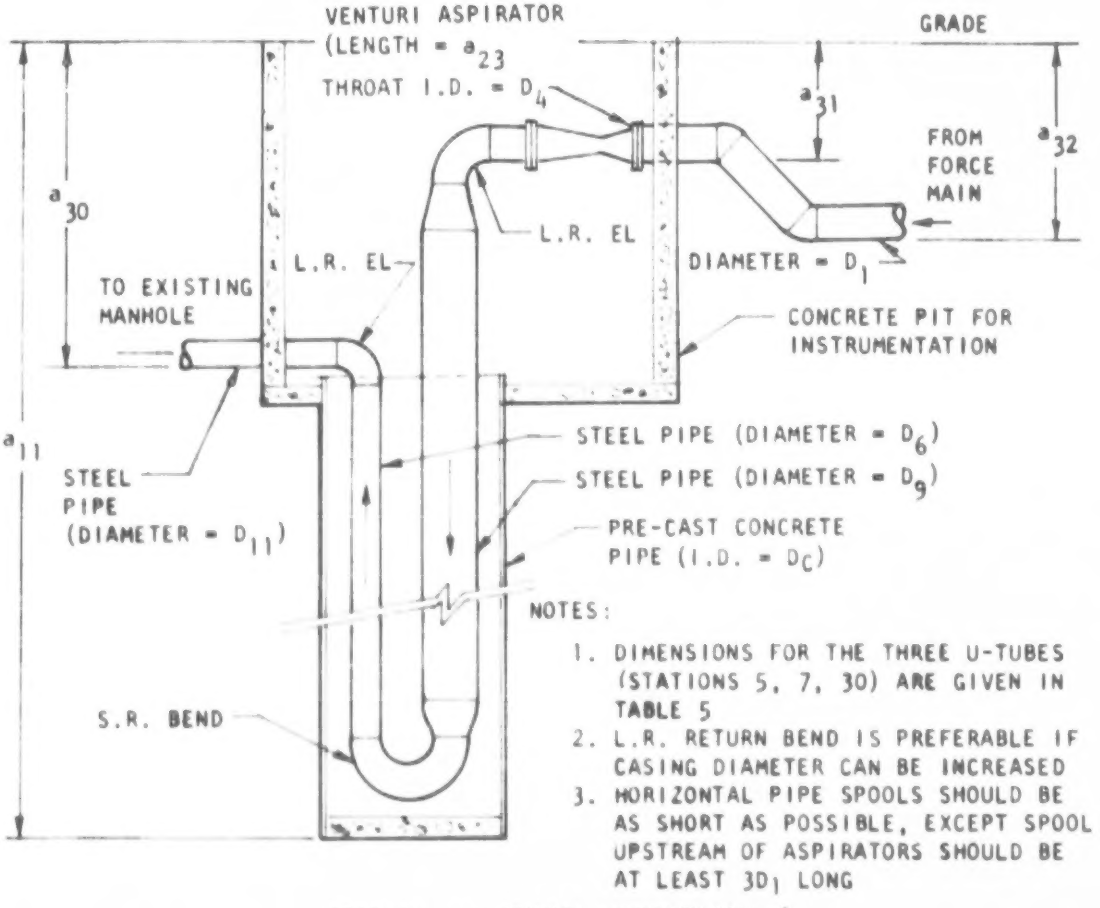
OPTIMIZATION STUDIES AND FINAL DESIGN FOR COMPRESSED-AIR U-TUBE

The design constraints for Station 9, at which a compressed air U-tube was to be installed, were previously given in Table 4. The basic configuration was previously shown in Fig. 30 and is similar to that chosen for the aspirated-air U-tubes, although the specific final design for Station 9 had the air injector ring at the top of the downleg rather than in the generalized location shown in Fig. 30. The compressed-air U-tube also used a literal U-bend return to eliminate possibilities for plugging at the bottom of the system.

Many parametric design cases were analyzed with the design computer program. Some of the results are plotted in Fig. 42 through Fig. 46. Most of the trends are similar to those predicted for aspirated-air U-tubes. One notable exception is the crossing-over of the curves for various casing depths in Fig. 44. This is caused both by the specific requirements of Station 9 and the nature of the compressed-air U-tube. The results show that a deeper U-tube does not necessarily result in improved performance for the compressed-air U-tubes at Station 9. For example, at a fixed overall pressure drop of 4 ft the exit D.O. concentrations are 3.7, 3.4, and 3.0 mg/l for 30, 40, and 50 ft casings, respectively.


EXISTING FORCE MAIN
EXISTING MANHOLE
VALVES
A
A

SITE PLAN


VENTURI ASPIRATOR (LENGTH = a23
THROAT I.D. = D4
GRADE
a31
a32
FROM FORCE MAIN
a30
L.R. EL
L.R. EL
DIAMETER = D1
TO EXISTING MANHOLE
CONCRETE PIT FOR INSTRUMENTATION
a11
STEEL PIPE (DIAMETER = D6)
STEEL PIPE (DIAMETER = D9)
STEEL PIPE (DIAMETER = D11)
PRE-CAST CONCRETE PIPE (I.D. = DC)
S.R. BEND

NOTES:

1. DIMENSIONS FOR THE THREE U-TUBES (STATIONS 5, 7, 30) ARE GIVEN IN TABLE 5
2. L.R. RETURN BEND IS PREFERABLE IF CASING DIAMETER CAN BE INCREASED
3. HORIZONTAL PIPE SPOOLS SHOULD BE AS SHORT AS POSSIBLE, EXCEPT SPOOL UPSTREAM OF ASPIRATORS SHOULD BE AT LEAST $3D_1$ LONG

SECTION A-A (SHOWN SCHEMATICALLY)

Figure 42. Aspirated-Air U-Tube Designs for Jefferson Parish Sewer System

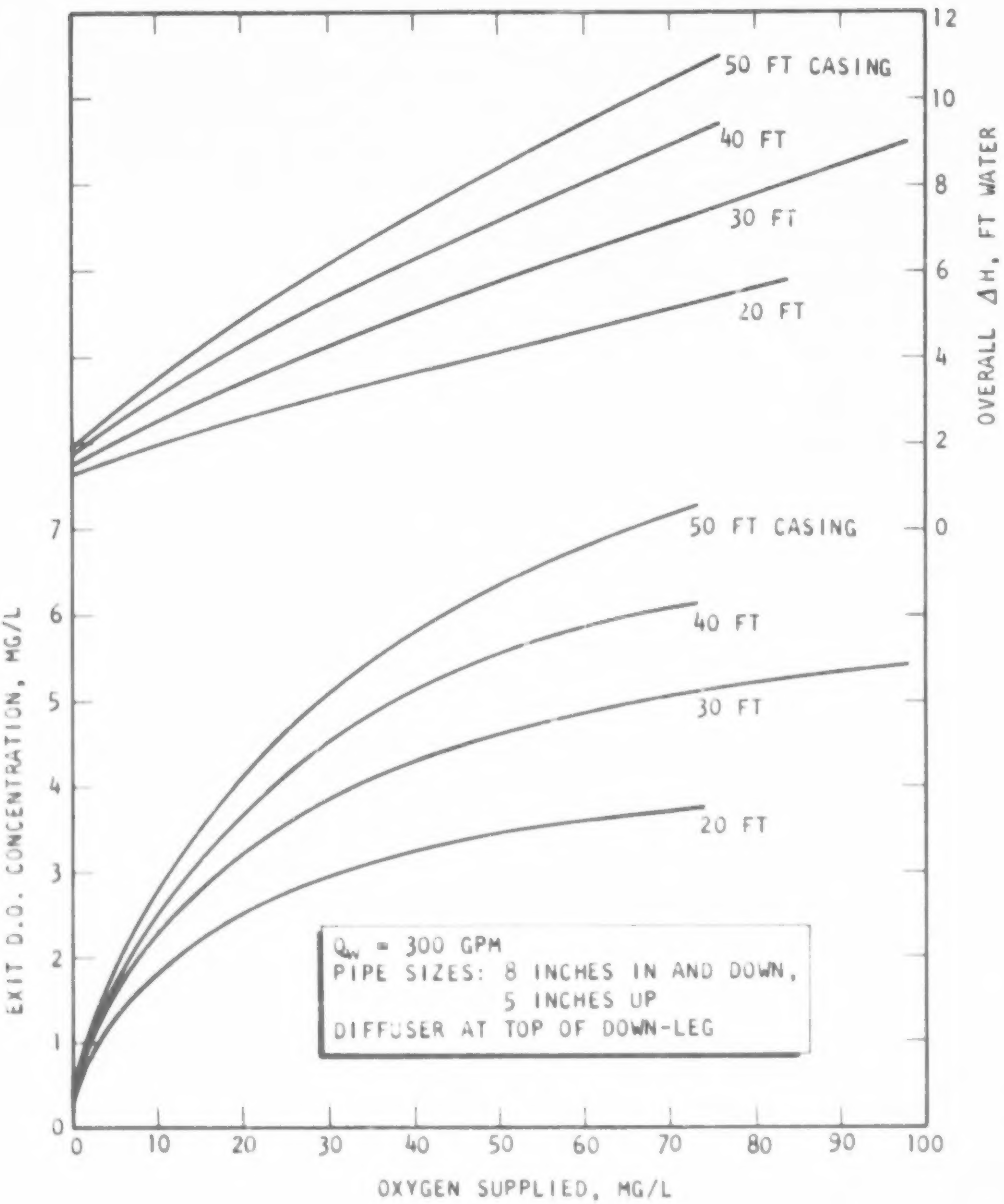


Figure 43. Compressed-Air U-Tube Parametric Designs for Station 9

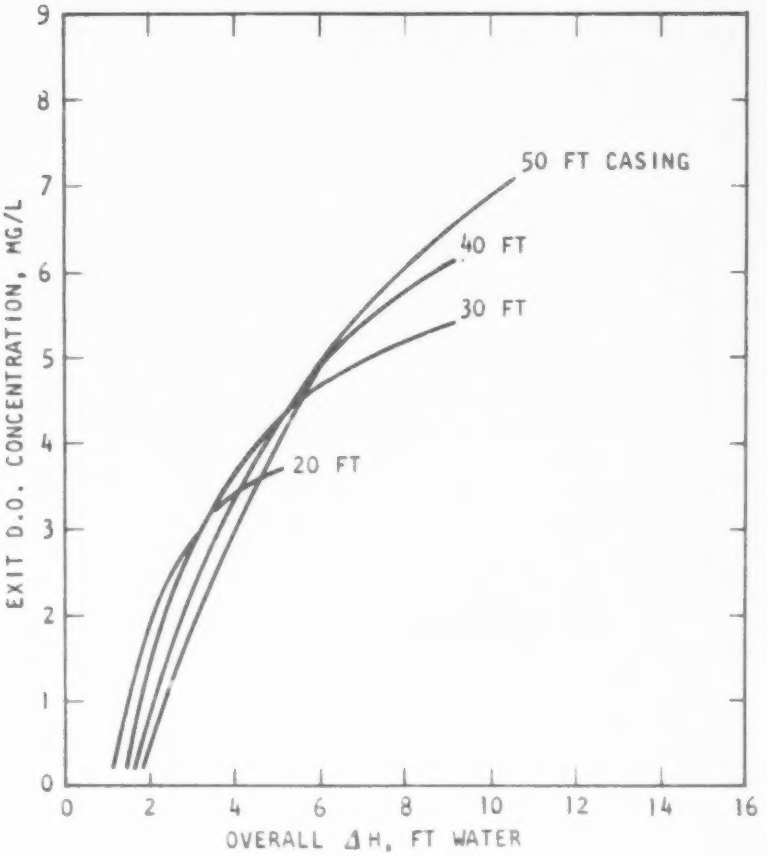


Figure 44. Compressed-Air U-Tube Design Trade-Offs for Station 9

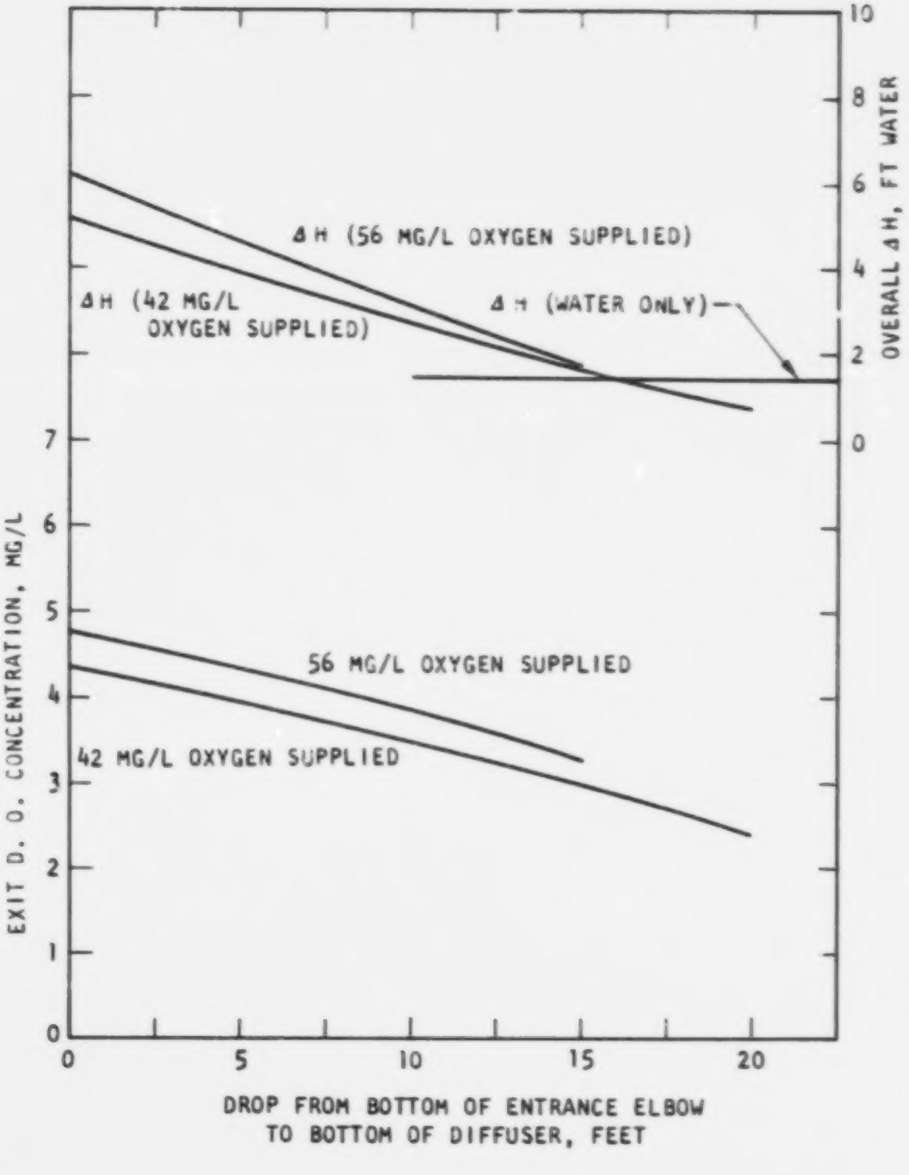


Figure 45. Effect of Diffuser Depth on Performance of Compressed-Air U-Tubes at Station 9

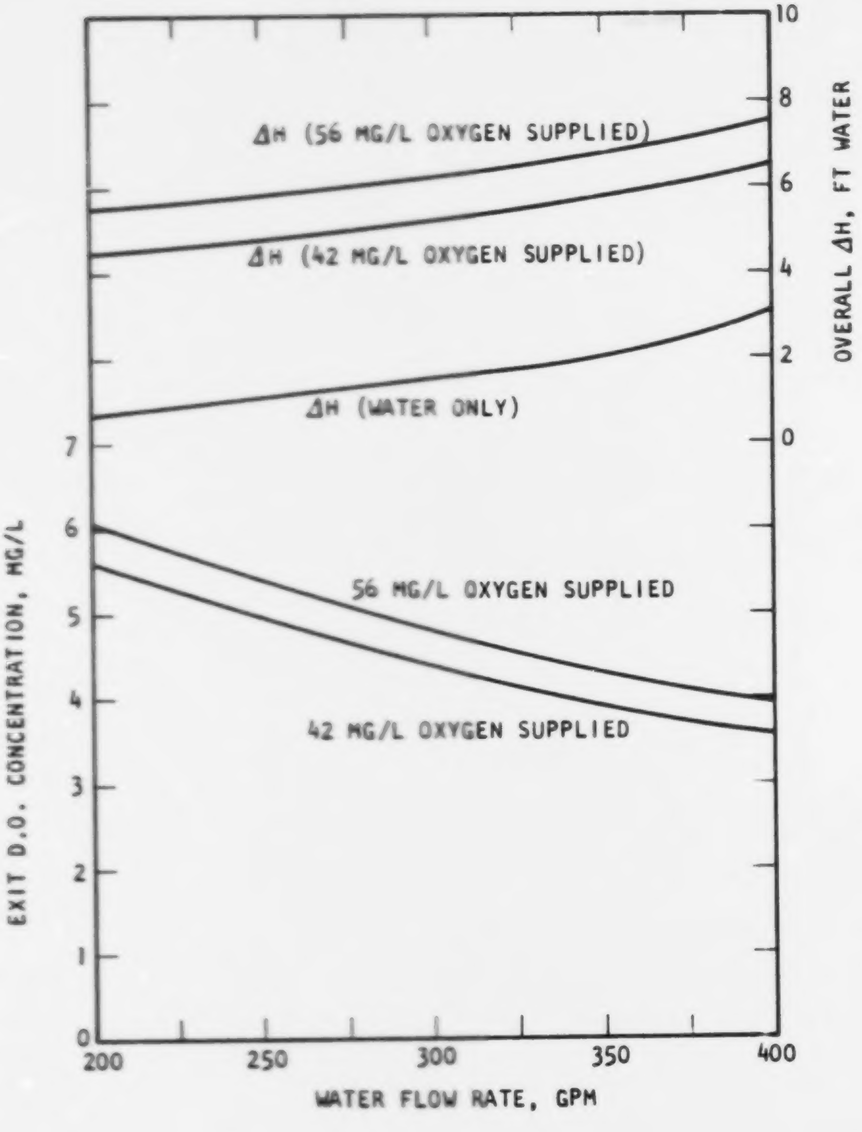


Figure 46. Effect of Water Flow Rate on Performance of Compressed-Air U-Tubes at Station 9

TABLE 5

ASPIRATED-AIR U-TUBE DESIGN PARAMETERS

Site station number	5	7	30
Water flow rate (gpm)	1800	670	1000
Entrance pipe size, D_1* (in)	12	10	8
Down-leg pipe size, D_6 (in)	20	12	16
Up-leg pipe size, D_9 (in)	14	8	10
Exit pipe size, D_{11} (in)	14	8	10
Venturi Throat diameter, D_4 (in)	6.40	4.00	4.00
Venturi length, a_{23} (in)	24	21	21
Casing I.D. (in)	47	35	35
Depth to casing bottom, a_{11} (ft)	45	35	35
Depth to exit pipe invert, a_{30} (ft)	11	9	9
Depth to aspirator pipe invert, a_{31} (in)	20	17	15
Depth to entrance pipe invert, a_{32} (ft)	4	5.5	9

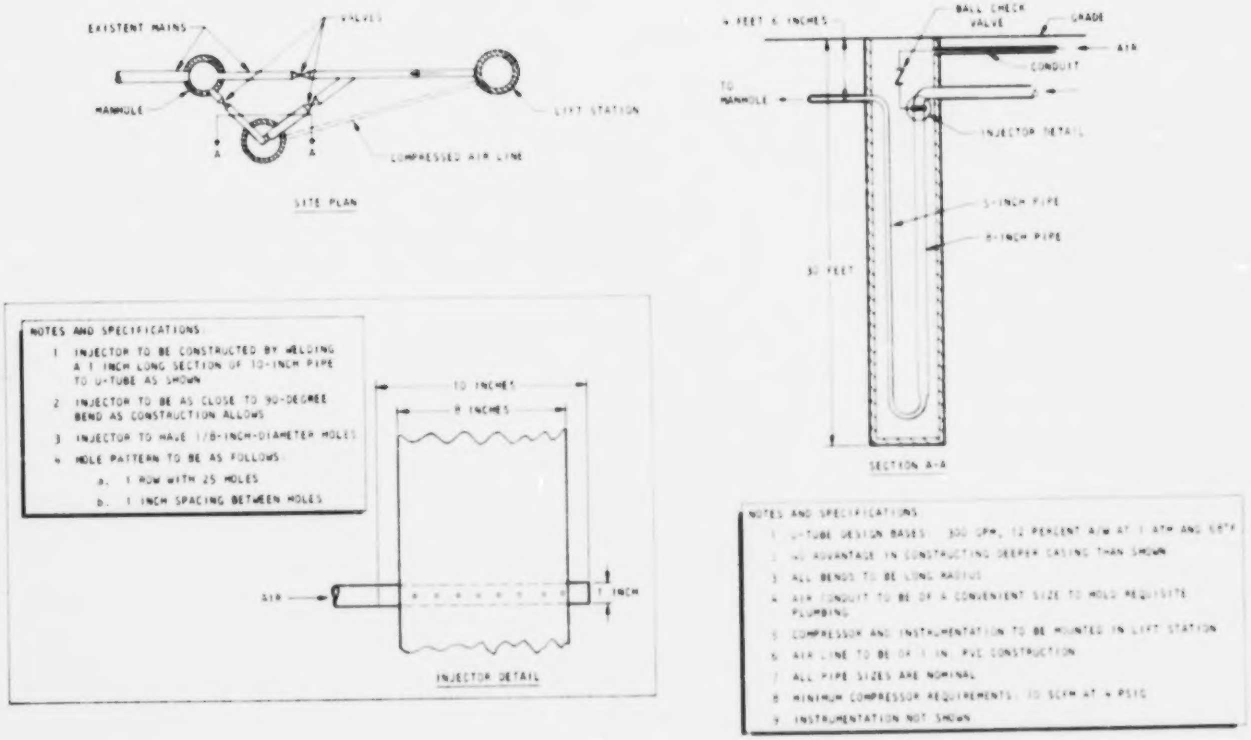
*See Figure 42 for system configuration and identification of dimension variables listed in this table

The final design parameters and details are shown in Table 6 and Fig. 47. These were selected after consideration of the U-tube system and pump characteristics, design constraints, and costs.

TABLE 6

COMPRESSED-AIR U-TUBE DESIGN PARAMETERS (STATION 9)

Water flow rate (gpm)	300
Entrance pipe size, D_1 (in)	8
Down-leg pipe size, D_6 (in)	8
Up-leg pipe size, D_9 (in)	5
Exit pipe size, D_{11} (in)	5
Casing I.D. (in)	30
Depth to casing bottom, a_{11} (ft)	30
Depth to entrance pipe invert, a_{32} (ft)	4.5
Depth to exit pipe invert, a_{30} (ft)	4.5


EXISTENT MAINS
VALVES
MANHOLE
LIFT STATION
A
A
COMPRESSED AIR LINE
SITE PLAN
4 FEET 6 INCHES
BALL CHECK VALVE
GRADE
AIR
CONDUIT
TO MANHOLE
INJECTOR DETAIL
5-INCH PIPE
8-INCH PIPE
30 FEET
SECTION A-A
10 INCHES
8 INCHES
AIR
1 INCH
INJECTOR DETAIL

NOTES AND SPECIFICATIONS:

1. INJECTOR TO BE CONSTRUCTED BY WELDING A 1 INCH LONG SECTION OF 10-INCH PIPE TO U-TUBE AS SHOWN
2. INJECTOR TO BE AS CLOSE TO 90-DEGREE BEND AS CONSTUCTION ALLOWS
3. INJECTOR TO HAVE 1/8-INCH-DIAMETER HOLES
4. HOLE PATTERN TO BE AS FOLLOWS:
   a. 1 ROW WITH 25 HOLES
   b. 1 INCH SPACING BETWEEN HOLES

NOTES AND SPECIFICATIONS:

1. U-TUBE DESIGN BASES: 300 GPM, 12 PERCENT A/W AT 1 ATM AND 68°F
2. NO ADVANTAGE IN CONSTRUCTING DEEPER CASING THAN SHOWN
3. ALL BENDS TO BE LONG RADIUS
4. AIR CONDUIT TO BE OF A CONVENIENT SIZE TO HOLD REQUISITE PLUMBING
5. COMPRESSOR AND INSTRUMENTATION TO BE MOUNTED IN LIFT STATION
6. AIR LINE TO BE OF 1 IN. PVC CONSTRUCTION
7. ALL PIPE SIZES ARE NOMINAL
8. MINIMUM COMPRESSOR REQUIREMENTS: 10 SCFM AT 4 PSIG
9. INSTRUMENTATION NOT SHOWN

Figure 47. Compressed-Air U-Tube Design for Station 9, Jefferson Parish Sewer System

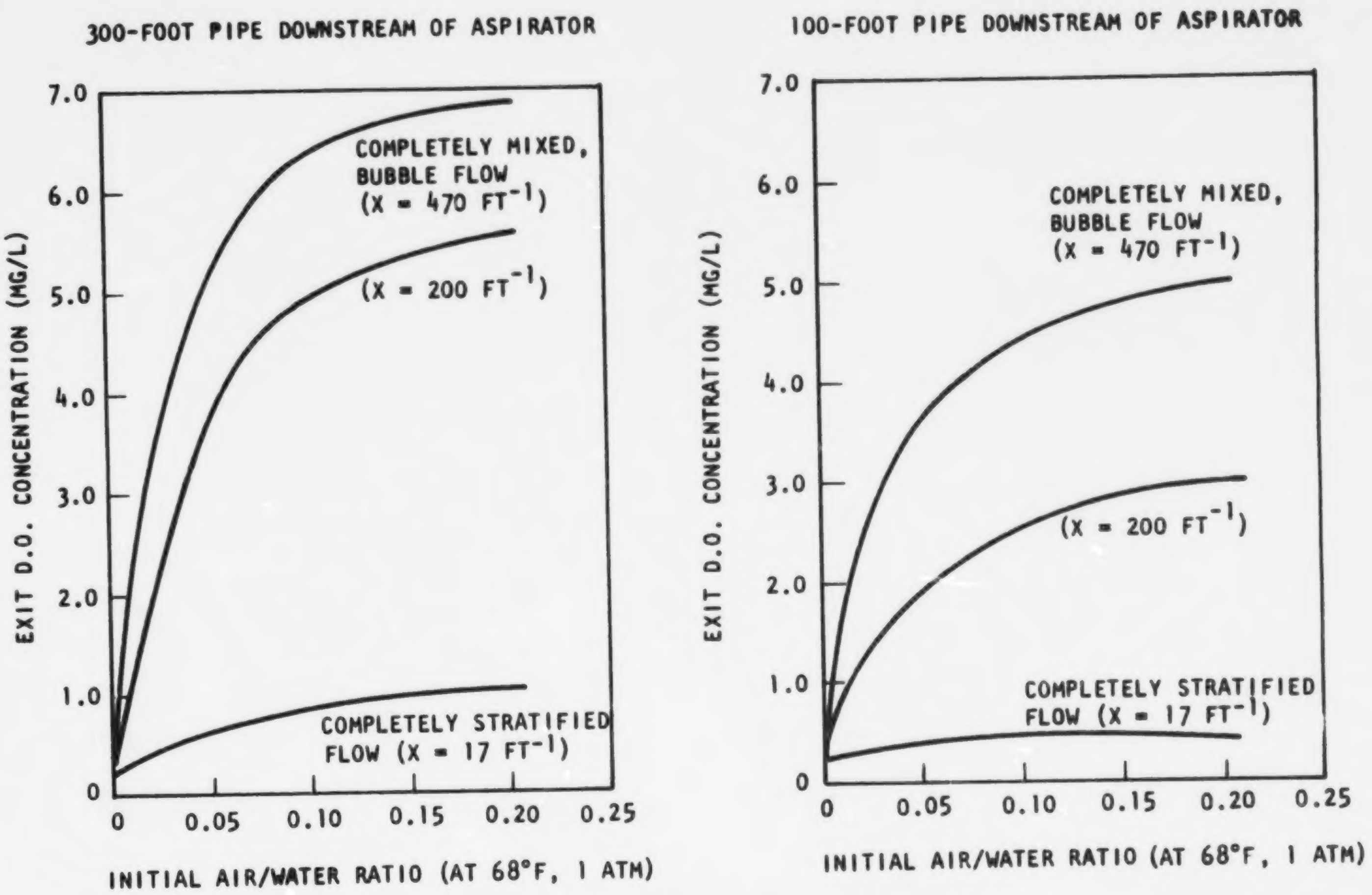
OPTIMIZATION STUDIES AND FINAL DESIGN FOR IN-LINE ASPIRATOR

Calculations and designs were made for a horizontal venturi aspirator located in the force main line at Station 31, which would be approximately 100 to 300 feet upstream of Station 30 in the existing 8-inch force main. This system is essentially an aspirated-air U-tube without the usual U-shaped tube downstream of the aspirator.

It was concluded that such an installation would not be practical if operated in series with the U-tube at Station 30, because the resulting back-pressure (i.e., pressure on the downstream side of the aspirator at Station 31) would require an excessively small venturi throat. However, such a system at Station 31 could be very practical if it were operated only when its discharge line was opened directly to the wet-well at Station 31, thus by-passing the U-tube at Station 30, and if the aspirator at Station 31 were raised at least several feet above the existing force main elevation.

One important unknown which could not be resolved is the rate at which the air-water mixture leaving the aspirator will stratify. This question requires applicable experimental data, but no remotely applicable data could be found. Figure 48 illustrates the importance of the amount of stratification, important primarily because of its large effect on the total air-water interfacial area. The top curve represents an upper limit to mass transfer (which would definitely not be reached), in which the air-water mixture is assumed to be completely mixed throughout the length of force main and to contain air bubbles of the size distribution observed in typical U-tube experiments. The bottom curves represent a lower limit to mass transfer, i.e., a case in which the air and water are completely separated (stratified) throughout the length of force main. The middle curves represent an arbitrary intermediate mean value of air-water interfacial area which seems reasonable for 100 ft of pipe, but which is probably optimistic for 300 ft of pipe.

The final design conditions chosen for this aeration installation are given in Table 7.



NOTES: Q = 1000 GPM, T = 82.4 F, P = 1 ATM, INLET D.O. = 0.2 MG/L, ASPIRATOR 4 FEET ABOVE GRADE, VARIOUS ASSUMPTIONS ON INTERFACIAL AREA PER UNIT BUBBLE VOLUME (X) AS SHOWN

Figure 48. Oxygen Transfer in Station 31 Aspirator and Downstream Force Main

TABLE 7

IN-LINE ASPIRATOR DESIGN PARAMETERS

Water flow rate (gpm)	1000
Line size (in)	8
Distance from grade to force main (ft)	4
Distance from grade up to aspirator center line (ft)	4 (approx.)
Distance from H56 wet-well upstream to aspirator (ft)	300 (approx.)
Aspirator throat diameter (in)	4.80
Aspirator contraction area ratio	2.77
Amount of air supplied (Vol. fraction air at 1 atm., 68° F)	0.2
Amount of oxygen supplied (mg/l)	56
Amount of oxygen dissolved (mg/l	1.5 to 3.0 (very approx.)
Increase in system head loss (ft water)	4 (approx.)

OTHER APPLICATION STUDIES AND ECONOMIC EVALUATIONS

Economic comparisons with current conventional aeration methods are essential in evaluating the potential of the U-tube for commercial application as an aeration device. The following predesign cost estimates were made without the benefit of firm pricing based upon detailed designs, in most cases, and consequently do not establish the absolute costs of the processes. However, these estimates give an approximate magnitude of the costs, in addition to their primary purpose of comparing the relative cost of U-tube aeration with various other aeration systems. These comparisons are made for two major applications: post-aeration of treated effluent, and in-situ aeration of sanitary sewers.

POST-AERATION OF TREATED EFFLUENT

Selection of Aeration Systems

Two commonly used systems, diffused-air and mechanical aeration, were selected for economic comparison with U-tube aeration. A prime consideration for diffused aeration is the type of diffuser to be used. The various types of available diffusers might be grouped into two categories: fine bubble dispersers (e.g., porous tubes), and coarse bubble dispersers (e.g., spargers). Choice of an air diffuser on the basis of oxygen transfer efficiency (oxygen dissolved/oxygen supplied) alone would lead to use of small bubble diffusers (see e.g., Ref. 16 and 17). However, because of the higher pressure and maintenance requirements for small bubble diffusers, spargers were selected as the diffuser type for this comparison. Plug flow (i.e., no mixing in the direction of flow) was assumed for the aeration tanks, since this would result in higher driving forces for mass transfer and, consequently, lower costs.

Mechanical or entrainment type aerators usually consist of a circular, flat plate with vertical blades or inclined vanes extending from the periphery of the plate. The plate rotates in a horizontal plane a short distance below the water surface and air is entrained by the blades of the turbine. Although other types of mechanical aerators have been described, this basic type of design was selected for this study.

U-tube aeration systems might have two basic return bend configurations: (1) separate down and up-legs with a connecting U-bend, or (2) concentric down-leg and up-leg. Also, a U-tube system might have a rectangular, rather than circular, flow cross-section. The selection of a configuration depends on the flow rate, the solids content of the stream, various site considerations (water table depth, soil composition, etc.) and construction considerations (construction material requirements, site access, etc.). For comparable in-tube velocities, air-to-water ratios, and depth, all configurations should perform essentially the same with respect to oxygen transfer.

The concentric design with circular flow cross-sections was selected for aeration of secondary effluent. For an actual application, the design selected would be based on the factors discussed above.

Design Bases

Oxygen absorption rates in secondary effluent as compared to the absorption rate in tap water must be known to determine aeration efficiencies. For oxygen in water, the rate of absorption is proportional to the difference between the saturated dissolved oxygen concentration and the actual dissolved oxygen concentration. Experimentally, rates of oxygen absorption are determined at standard conditions using the basic relationship:

$$\frac{dD}{dt} = -K\,(C_s - C) \qquad (23)$$

where D is the dissolved oxygen deficit (C_s-C), t is time, K is the overall mass transfer coefficient, C_s is the saturation concentration of oxygen in the liquid, and C is the actual concentration of oxygen in the liquid.

Standard conditions are usually defined as tap water at 20° C containing zero dissolved oxygen. A quantity alpha is defined as the ratio of K for a particular waste water to K for pure tap water. For this economic comparison, an alpha value of 0.9 was assumed (the value customarily used for secondary effluent by the FWPCA Robert A. Taft Water Research Center [18]).

Aeration devices (spargers, mechanical diffusers, etc.) are usually rated at a standard temperature. In order to convert these ratings to other temperature conditions, the relationship between the coefficient (K) and temperature must be known. The effect of temperature on K is usually represented by the following equation:

$$K_T = K_{20}(\theta)^{T-20} \qquad (24)$$

where K_T is the overall mass transfer coefficient at temperature T, K_{20} is the coefficient at 20° C, T is temperature in degrees centigrade, and θ is a constant. The constant θ has been evaluated by numerous investigators; a value of 1.024 was selected for this study.

Performance of aerators at non-standard operating conditions may be calculated with the following relationship, provided the performance at standard conditions is known:

$$N = \frac{N'\alpha(1.024)^{T-20}(D_1-D_2)}{C'_s \ln(D_1/D_2)} \qquad (25)$$

where N is the aerator performance rating (e.g., in lb oxygen/hp-hr), superscript prime refers to standard conditions, and subscripts 1 and 2 refer to initial and final conditions, respectively. This expression was used to calculate the efficiencies of a turbine type aerator and a sparger at several levels of final DO content. Standard condition values [19,20,21] are shown in Fig. 49 along with the efficiency curves for the two aeration methods. Mechanical aerators typically have higher power performance ratings (N) than diffused air systems; however, they also have higher capital, operating, and maintenance costs.

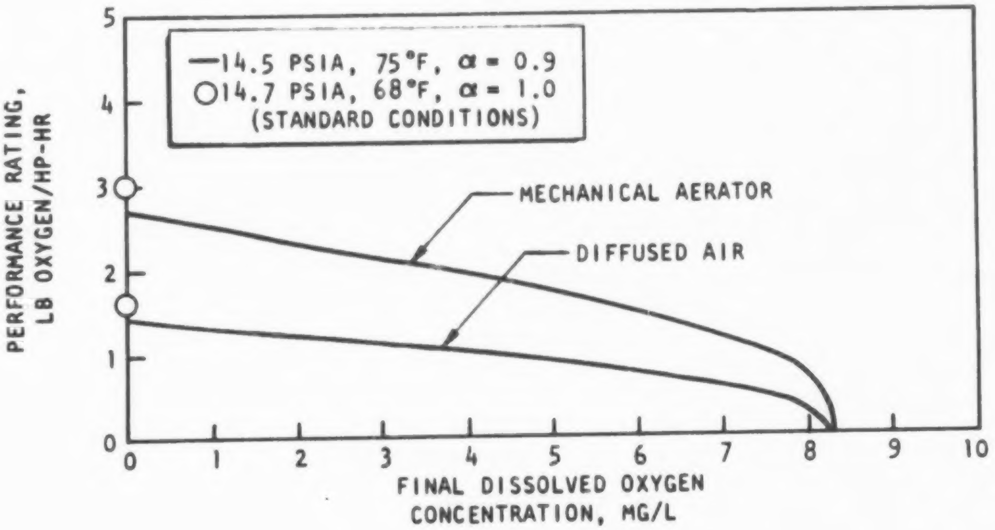


Figure 49. Effect of Final D.O. Concentration on Performance of Diffused Air and Mechanical Aeration Systems

U-tube sizing was done with the computer design program discussed previously. This program was derived by extending the data obtained from the 2-inch experimental U-tube to larger systems. Corrections for alpha and temperature (as previously discussed) were made by the program.

After selecting up- and down-leg velocities plus casing diameters, the U-tube depth was optimized. Optimization consisted of deriving operating lines (based on the computer printouts) of the form shown in Fig. 30

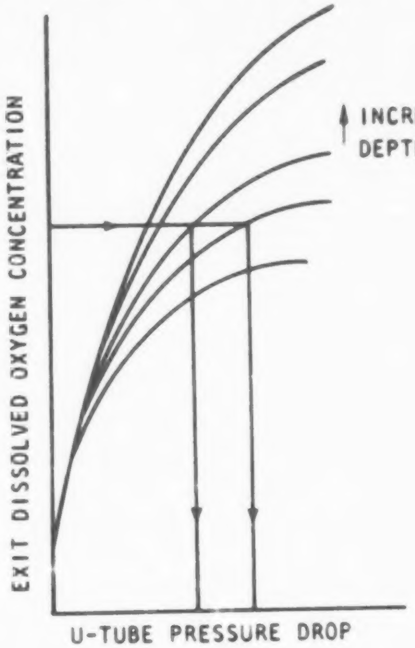


Figure 30. Schematic Diagram of U-Tube Operating Lines

for various casing depths ranging from 20 to 70 ft. For selected exit D.O. levels, each casing depth gave an associated U-tube ΔH (See Fig. 30). The amortized yearly cost of the U-tube plus the power required to pump the flow at a given ΔH was evaluated for each casing depth at a given exit D.O. An optimum casing depth (corresponding to optimum cost) was selected at several exit D.O. levels.

The primary physical and economic design bases used in these economic comparisons are summarized in Table 8.

Designs

The level of design detail in these economic comparisons was necessarily limited, consisting primarily of developing a conceptual design layout plus selection and sizing of the major process components. A plan view of the aeration basin for mechanical or diffused aeration is shown in Fig. 31 as an extension of an existing plant and secondary effluent discharge channel. The aeration basin or tank may utilize one wall in common with the outlet channel. However, for this cost

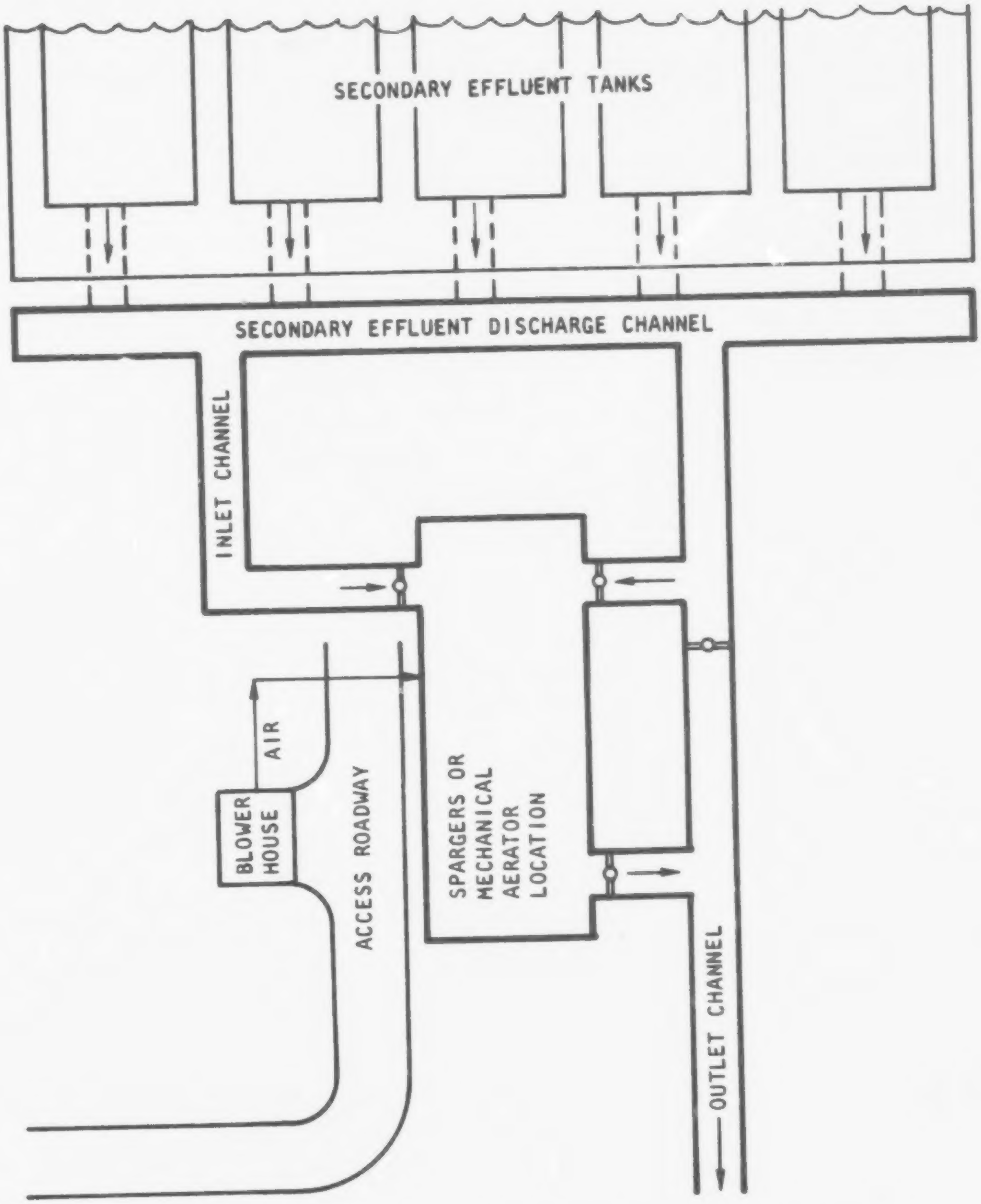

SECONDARY EFFLUENT TANKS
SECONDARY EFFLUENT DISCHARGE CHANNEL
INLET CHANNEL
AIR
BLOWER HOUSE
ACCESS ROADWAY
SPARGERS OR MECHANICAL AERATOR LOCATION
OUTLET CHANNEL

Figure 51. Schematic Layout of Diffused Air or Mechanical Aeration System for Post-Aeration of Treated Effluent

TABLE 8

SELECTED ECONOMIC AND PHYSICAL DESIGN BASES FOR AERATION SYSTEM COST ESTIMATES

1. Aeration plant flow rates of 10 mgd and 100 mgd.
2. Aeration installation is immediately downstream of the treatment plant, and laboratory facilities, proximate utilities and buildings are available.
3. Water temperature is 75° F.
4. Ambient pressure is 14.5 psia.
5. D.O. saturation level is 8.33 mg/l at 14.5 psia.
6. Incoming waste water (secondary treatment plant effluent) has 1.0 mg/l D.O.
7. $\alpha = \frac{\text{Oxygen transfer rate in effluent}}{\text{Oxygen transfer rate in tap water}} = 0.90.$
8. Capital costs amortized at 4.5 percent over 25 years.
9. Electrical power cost = $0.01/kw-hr.
10. Cost of land - $5,000 per acre.

comparison the basin was assumed to be a separate entity with one exception. The tank utilized for aerating water with spargers at a flow of 10 mgd was assumed to be incorporated into and form a portion of the outlet channel.

Characteristics of the diffuser and mechanical systems considered in this study are given by Table 9. Diffuser aeration of secondary effluent at 10 mgd utilized a depth of only 8 ft to nearly coincide with the depth of the outflow channel. At a sparger immersion of 6 ft the oxygen absorption is only 3.5 percent [19,20] as compared with an efficiency of 6.5 percent at a submergence of 12 ft. However, the number of spargers is well within reason and, in essence, permits aeration within a section of modified channel. For the higher secondary effluent flow rate (100 mgd), an aeration tank or basin is utilized and the depth of sparger submergence is increased to 12 ft to take advantage of the increased oxygen absorption efficiency at greater depths.

Basin designs for mechanical aeration of secondary effluent have been limited to a depth of 7 ft to ensure adequate air entrainment and water circulation required for achieving design efficiencies. Aeration tanks are sized for mechanical surface aerators and in particular for the Turborator* [21] manufactured by the Chicago Pump Company. The

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*Mention of a commercial product does not imply endorsement by either Rocketdyne or the Federal Water Pollution Control Administration.

TABLE 9

SYSTEM CHARACTERISTICS FOR DIFFUSED-AIR AND MECHANICAL AERATION

Final D.O. Concentration, Percentage of Saturation	30	45	60	75	90
Diffused Aeration					
10 mgd					
Tank Size (ft)	31x10x8	34x10x8	38x10x8	42x10x8	45x10x8
No. Spargers	9	16	24	32	38
Air Required (scfm)	132	242	351	484	572
100 mgd					
Tank Size (ft)	50x24x15	57x24x15	60x24x15	64x24x15	66x24x15
No. Spargers	40	72	104	144	170
Air Required (scfm)	584	1075	1560	2145	2540
Mechanical Aeration					
10 mgd					
Tank Size (ft)	20x10x7	20x10x7	30x20x7	30x20x7	30x25x7
Aerator*	Model 1000	Model 1000	Model 1750	Model 1750	Model 2000
Oxygen Dissolution Rate (lb/hr)	8	15	36	44	70
100 mgd					
Tank Size (ft)	35x30x7	35x30x7	50x30x7	60x40x7	90x50x7
Aerator*	Model 2500	Model 2500	1 Model 2500 1 Model 1000	2 Model 2500	1 Model 100 3 Model 250
Oxygen Dissolution Rate (lb/hr)	73	146	251	443	696

*Chicago Pump Company mechanical aerator model numbers availability of adequate performance characteristics was the only reason for considering this surface aerator rather than some other commercial design.

The conceptual plan for U-tube aeration in 10 mgd plant is shown in Fig. 52. The plan for the 100 mgd plant is essentially the same except that there are 3 surge basins with a total of 11 U-tubes (split 4,3,4 between the basins). The choice of eleven 9-mgd U-tubes was based on the rather arbitrary selection of 3 ft as a maximum down-leg pipe diameter. This choice resulted in comparatively high costs for the U-tube systems at the 100 mgd flow rate. It would probably be much more efficient to use a U-tube with a wide, rectangular flow cross-section (which will still keep the aspirator throat smallest dimension from becoming too large for efficient air-water mixing. With such a configuration, the 100 mgd flow would probably be divided into two streams, flowing through two such U-tubes, for flexibility in operation. Characteristics of the non-optimized 10 and 100 mgd U-tube systems are described below:

1. Surge basins are 4 ft deep and provide approximately 650 gallons surge capacity per mgd.

2. 10 mgd U-tubes have a capacity of 5 mgd each, are 3 ft in diameter, and have the following depths:

Exit D.O. (mg/l)	Depth (ft)
2.50	20
4.16	40
5.83	50
7.50	60

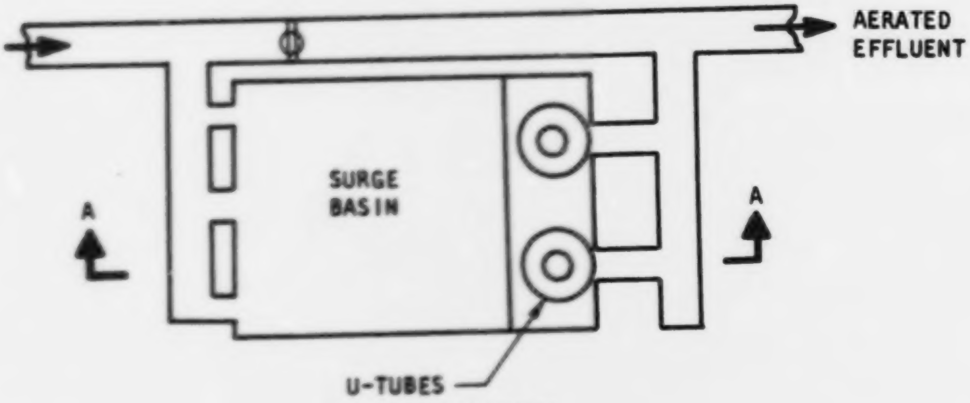
3. 100 mgd U-tubes have a capacity of 9 mgd each, are 4.5 ft in diameter (3 ft down-leg pipe), and have the following depths:

Exit D.O. (mg/l)	Depth (ft)
2.50	20
4.16	40
5.83	50
7.50	60

4. U-tube materials are assumed to be: Venturi - poured concrete; Down-leg - steel pipe; Up-leg (casing) - concrete pipe

Economic Comparison of Secondary Effluent Aerators

Many of the primary cost bases were summarized in Table 8 given in a previous sub-section. Total direct plant costs (including contractor's fee, engineering and legal fees) were evaluated as 135 percent of


AERATED EFFLUENT
SURGE BASIN
A
A
U-TUBES

PLAN VIEW

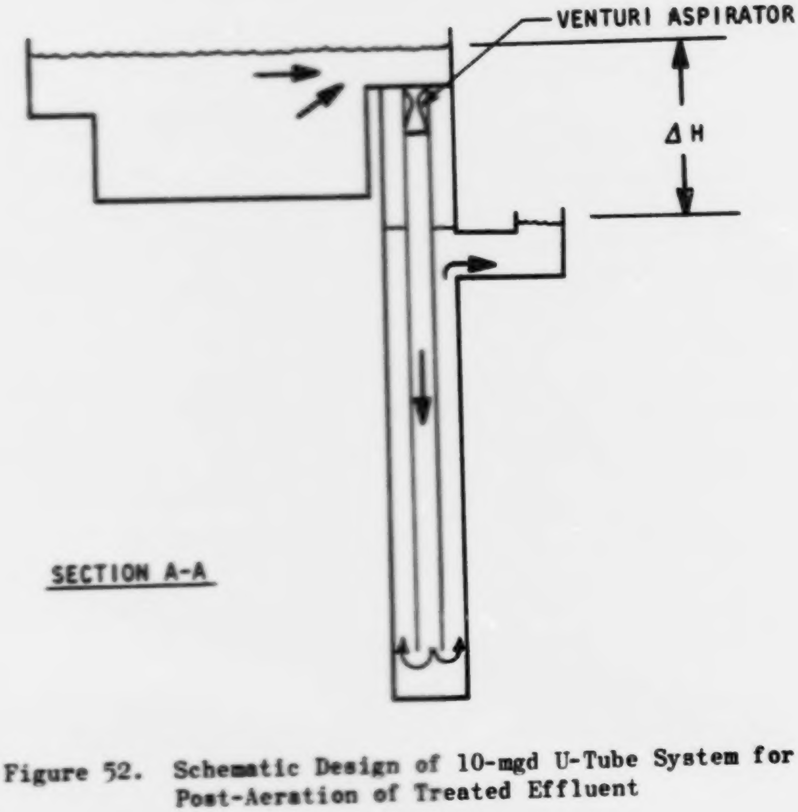

VENTURI ASPIRATOR
Δ H
SECTION A-A

Figure 52. Schematic Design of 10-mgd U-Tube System for Post-Aeration of Treated Effluent

physical plant costs. Fixed capital costs were taken as 110 percent of the direct plant costs (10 percent contingency) and amortized over 25 years at 4.5 percent. Factors such as maintenance, operating labor, plant overhead, and administrative costs were considered in the estimates.

The major constituents of the physical plant costs are given in Table 10.

TABLE 10

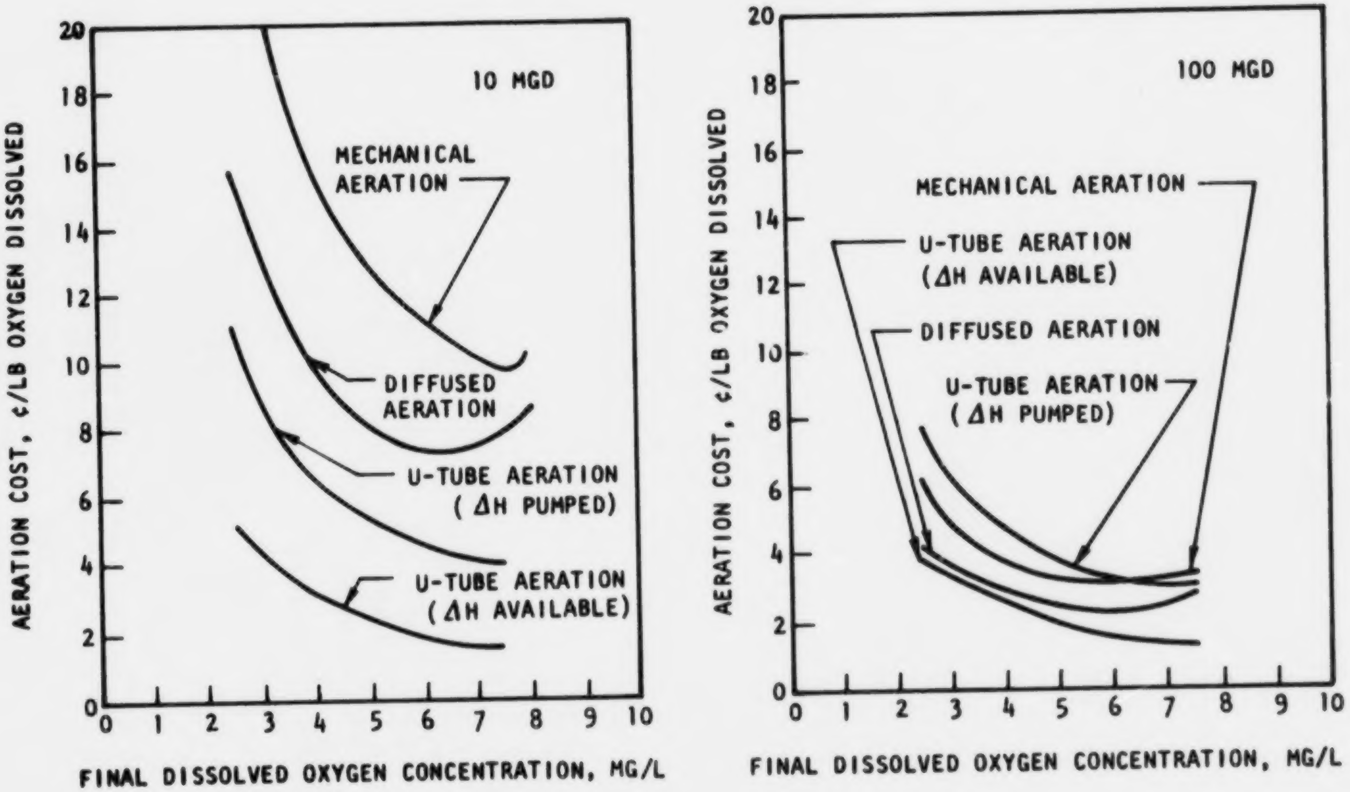
MAJOR PHYSICAL PLANT COSTS

DIFFUSED AND MECHANICAL AERATION	U-TUBE AERATION
Aeration Device	U-Tube
Aeration Tank	Surge basin
Effluent channel	Secondary effluent and discharge channels
Tank drain, pump system	Sidewalks
Flow gates or wiers	Pumps and motors
Control, switching and lighting	Excavation
Bridge and aerator support (mechanical only)	Installation
Blower, blower house and air piping (diffused only)	Land
Excavation	
Installation	
Land	

Major equipment costs such as mechanical aerators, pumps, and motors were based on manufacturers' quotes. Estimates of concrete construction, air and water piping, excavation, and other similar costs were obtained from standard sources of cost data (e.g., References 22 and 23).

In this study, aeration costs are presented as cost per weight of dissolved oxygen. This basis was selected because it can be readily applied to all three aeration systems. Mechanical and diffused aeration systems are not readily comparable[17] except for individual cases based on a realistic set of selected conditions which permit a determination of the total cost per unit of oxygen transferred. Efficiencies of diffused air systems are customarily defined in terms of oxygen transfer efficiency, whereas, efficiencies of mechanical aerators are stated in terms of the oxygen transferred to the liquid per unit of power input. The cost per unit weight of oxygen dissolved parameter provides a meaningful, common basis for comparing different types of aeration systems.

A cost comparison for all three systems is shown in Fig. 53 for 10 mgd and 100 mgd flow. Table 11 presents more detail for several cases. Two sets of values are given for U-tube aeration cost at each



BASES: p = 14.5 PSIA, T = 75° F, SAT. D.O. = 8.33 MG/L,
INITIAL D.O. = 1.0 MG/L, α = 0.9

Figure 53. Cost Comparisons for Post Aeration of Treated Effluent

TABLE 11

COST COMPARISON FOR POST-AERATION OF TREATED EFFLUENT

Total Flowrate (mgd)	Exit D.O. Concentration (% saturation)	Cost Component	Aeration Cost (cents/lb oxygen)			
			U-tube (ΔH available)	U-tube (Δ pumped)	Diffused Aeration	Mechanical Aeration
10	30	Amortized Capital	2.2	3.6	5.4	6.4
		Maintenance	0.9	2.5	2.9	6.4
		Operation	2.1	3.7	5.4	14.7
		Power		1.2	1.4	0.6
		TOTAL	5.2	11.0	15.1	28.1
10	60	Amortized Capital	1.3	1.9	2.8	3.3
		Maintenance	0.3	0.8	1.6	3.4
		Operation	1.0	1.5	2.3	6.2
		Power		1.1	1.6	0.5
		TOTAL	2.6	5.3	8.3	13.4
10	90	Amortized Capital	0.9	1.2	2.2	2.3
		Maintenance	0.2	0.5	1.3	2.6
		Operation	0.5	1.0	1.6	4.2
		Power		1.3	2.8	0.8
		TOTAL	1.6	4.0	7.9	9.9
100	30	Amortized Capital	2.2	3.1	1.4	1.4
		Maintenance	0.5	1.4	0.7	1.3
		Operation	1.3	2.2	1.6	3.1
		Power		1.1	0.5	0.4
		TOTAL	4.0	7.8	4.2	6.2

TABLE 11 (CONT'D)

Total Flowrate (mgd)	Exit D.O. Concentration (% saturation)	Cost Component	Aeration Cost (cents/lb oxygen)			
			(ΔH Available)	U-tube (Δ pumped)	Diffused Aeration	Mechanical Aeration
100	60	Amortized Capital	1.2	1.5	0.8	0.6
		Maintenance	0.2	0.6	0.4	0.9
		Operation	0.5	0.8	0.7	1.5
		Power		0.9	0.7	0.4
		TOTAL	1.9	3.8	2.6	3.4
100	90	Amortized Capital	0.9	1.1	0.6	0.7
		Maintenance	0.2	0.4	0.4	0.8
		Operation	0.3	0.5	0.5	1.1
		Power		1.0	1.2	0.8
		TOTAL	1.4	3.0	2.7	3.4

capacity. One assumes that the required head loss is available and that no pumping equipment or pumping costs are considered ("ΔH available"). The other curve ("ΔH pumped") includes the power, pumps, and all equipment needed to supply the required head loss.

It is apparent that the U-tube is a highly attractive aerator for both small and large capacities when the necessary driving force (ΔH) is available. Even if the ΔH must be achieved by pumping, the U-tube is the most economical system at 10 mgd. The reason is that at 10 mgd the amortized capital, maintenance, and operating costs per pound of dissolved oxygen are considerably higher for diffused and mechanical aeration systems than for U-tubes. The addition of pump, motor, and associated power costs to the U-tube system does not offset this difference.

At 100 mgd, Fig. 53 shows a smaller cost advantage for the U-tube - due, in large measure, to the design assumption of eleven 9-mgd U-tubes. With this assumption, diffused aeration is almost competitive with the U-tube for D.O. levels less than 5 mg/l. The estimated cost of mechanical aeration is also very similar.

If it is desired to convert these cost figures to annual costs, this can be easily accomplished by multiplying them by the pounds of oxygen transferred per year, e.g., at 10 mgd:

Exit D.O. Concentration (Percentage of Saturation)	Lb Oxygen Transferred Per Year
30	45,700
60	122,000
90	198,000

It is interesting to note that the estimated costs for mechanical aeration are higher than for diffused aeration even though the power performance ratings for diffused air systems are considerably lower. Higher estimated costs for operating and maintaining mechanical aerators are primarily responsible for this. As specific cost data on operating and maintenance expenses become available, these cost components can be established with greater certainty. In the meantime, users can easily modify these cost estimates by using different ground rules.

IN-SITU AERATION OF SANITARY SEWERS

Four concepts for in-line aeration of sanitary sewers were selected for economic comparison: (1) an aspirated-air U-tube at the end of a force main; (2) an aspirated-air U-tube in a gravity flow line; (3) a compressed-air U-tube in a force main; and (4) an eductor station. Three of the four systems have been proposed for the Jefferson Parish Upstream Aeration Project.

The cost analyses were based on construction cost bid prices received by Jefferson Parish for this project.[24] A flowrate of 3 mgd (2085 gpm) was assumed as a basis, and construction estimates for smaller systems were increased using a plant scale factor approach. Cost per pound of dissolved oxygen was evaluated for point values of exit D.O. based on: (1) Jefferson Parish design points for the aspirated-air and diffused-air U-tubes; (2) secondary effluent U-tube operating lines (Fig. 50 above) for the gravity flow U-tube; and (3) oxygen transfer estimates for the eductor station. Although the estimates do not establish absolute costs of the processes, they do give a comparison of relative costs of the four systems. Care should be taken in extrapolation of construction costs to other locations because of sub-surface soil characteristics and availability of specialized construction equipment.

One significant design concern in a sewer aeration application is preventing plugging problems. Consequently, a preliminary discussion of this topic is given in the next sub-section, before describing the preliminary designs and economic comparisons.

Solution to Silting and Plugging Problems

The significant factors to be considered upon approaching this problem are the types of solids present, the size range of the solids, the size of particle that will be flushed through the U-tube (for a fixed design), and the techniques for excluding very large solids from the U-tube. Raw sewage contains a variety of solid materials including largely non-settleable solids; light organic solids which are apt to be flushed through any U-tube system; sand and fine gravel; coarse gravel and stones; and other material such as rags, string, and plastic or rubber household articles. With respect to possible U-tube plugging, the primary concern is with sand, gravel, stones, and the other dense materials.

Fixing the U-tube size and flowrate will determine the maximum size particle of a given density which will be flushed through the system. The minimum water velocity required to prevent sedimentation and the velocity required to scour, once sedimentation has occurred, were both discussed in the Experimental Results section under Silting Studies. It was shown that current state-of-the-art does not permit determination of an exact a priori design velocity. However, estimates of safe flushing velocities can be made for a given particle size. More precise determination of allowable particle size will require more extensive scouring studies. Once the maximum size of particles which will be transported through the system is established for a specific case, it will only be necessary to exclude larger particles from the U-tube.

There are two types of solutions to the problem of solids exclusion: (1) solids can be removed prior to entering the U-tube facility or (2) solids can by-pass the U-tube and continue onward in the downstream sewer line. A number of hand cleaned or mechanically cleaned racks and screens are commercially available. Some of these units will collect waste matter down to 1/16 inch in size. Although a rack or screen will readily prevent the plugging problem, there are several drawbacks to this solution. A rack or screen implies additional head loss which must be considered in the ΔH requirement of the facility. Significant additional facility costs will be incurred for sewer line modification and for purchase of the equipment. Inclusion of a rack or screen increases maintenance requirements considerably and, hence, suppresses one of the major attributes of the U-tube.

It is apparent that an effective solids by-pass concept has many advantages over removal of the solids at the site. One possibility for effecting by-pass is the inclusion of a wire bodied section of sewer line (with a weir at one end) over the U-tube entrance, as depicted in Fig. 54. The face of the weir would be open at the bottom, allowing a small fraction of flow to carry large solids along the solid bottom of the screened section into the downstream line. If full-flowing sewers are anticipated, the screened section could be made a full cylinder. The weir would be appropriately sized to divert the desired fraction of flow into the U-tube. The screen would very possibly be self cleansed at periods of peak flow.

Another possible arrangement for by-passing solids is the use of a conveyer screen which is installed so that it is automatically backflushed by the waste water leaving the U-tube. This concept is shown schematically in Fig. 55. This arrangement would require a high velocity stream at the U-tube exit. This high velocity exit would require additional head, but it should enable the screen to operate with little maintenance. Of course, the conveyor would require power which would add to operating costs.

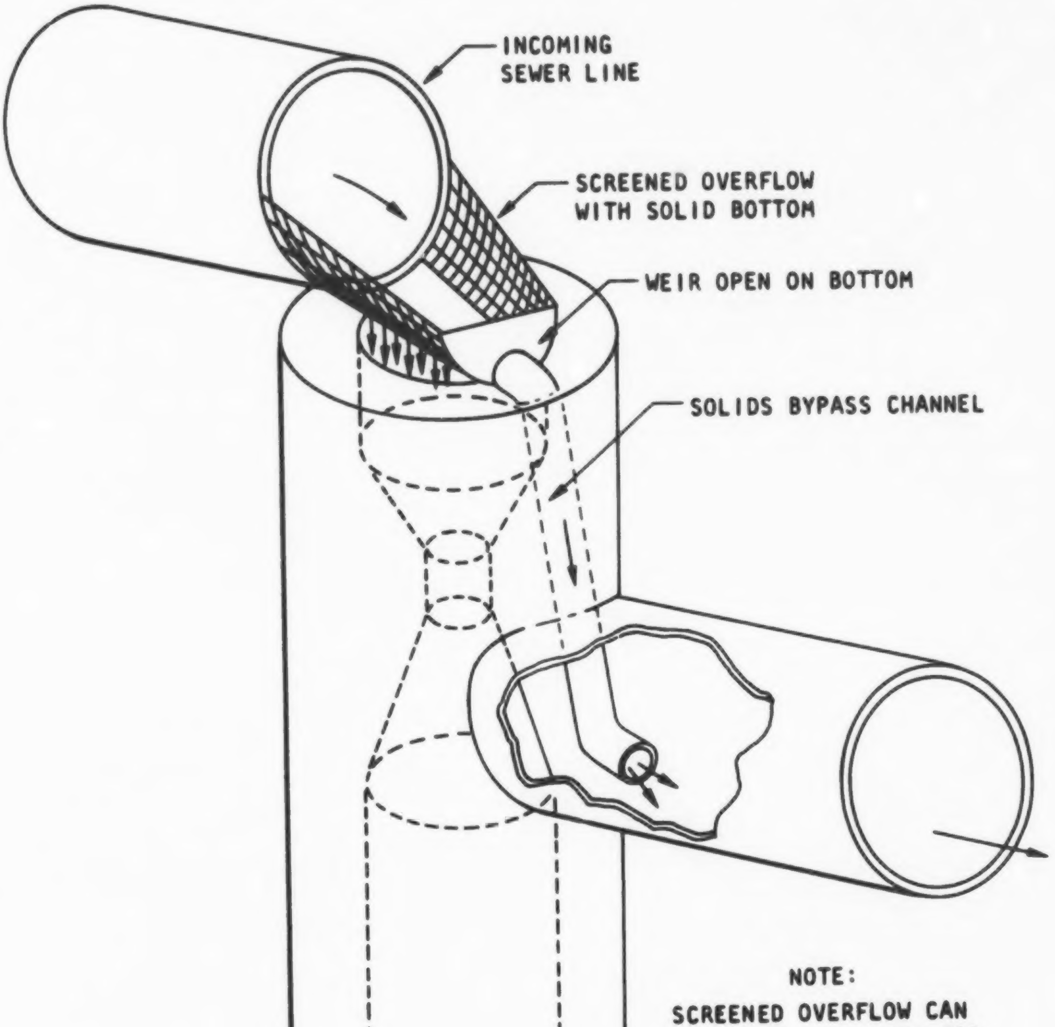
Although these designs are cursory in nature, they do demonstrate that the problem is by no means insurmountable. Additional effort in this area could bring about improvement on these preliminary concepts as well as other ideas for solids by-pass systems.

Cost and Design Bases

The following physical bases were assumed for all systems:

Inlet D.O. = 0.2 mg/l
α = 0.8
Q = 2085 gpm (continuous operation)
T = 28° C (82.4° F)
p = 1 atmosphere
C_s = 7.84 mg/l at 1 atm

In addition to these general bases, Table 12 gives some assumptions made on the individual systems.


INCOMING SEWER LINE
SCREENED OVERFLOW WITH SOLID BOTTOM
WEIR OPEN ON BOTTOM
SOLIDS BYPASS CHANNEL

NOTE:
SCREENED OVERFLOW CAN BE A FULL CYLINDER FOR ANTICIPATED FULL FLOW. WEIR MUST BE APPROPRIATELY SIZED

Figure 54. Solids By-Pass Conduit for U-Tube in Gravity Main

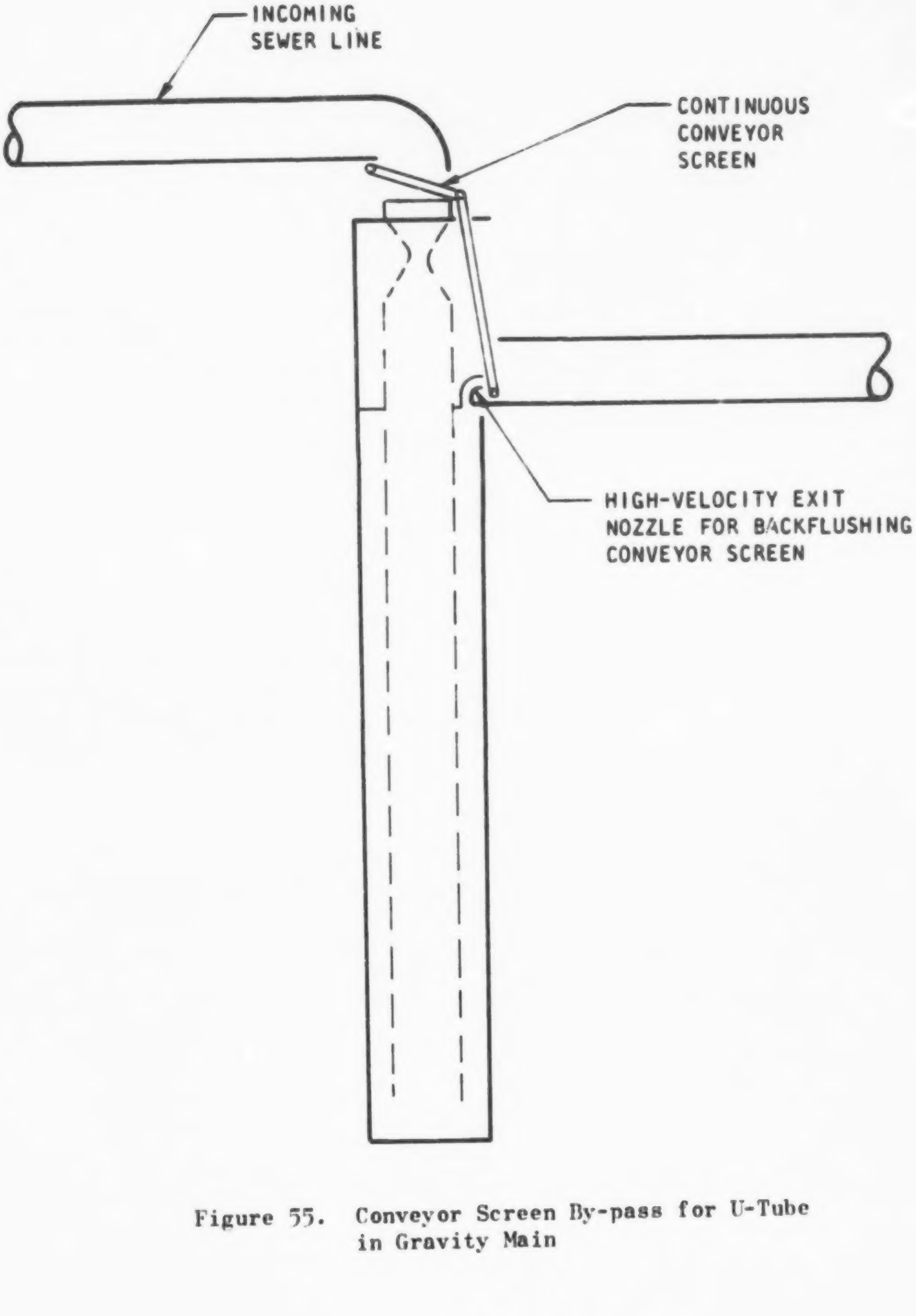

INCOMING
SEWER LINE
CONTINUOUS
CONVEYOR
SCREEN
HIGH-VELOCITY EXIT
NOZZLE FOR BACKFLUSHING
CONVEYOR SCREEN

Figure 55. Conveyor Screen By-pass for U-Tube in Gravity Main

TABLE 12

IN-SITU AERATION SYSTEM DESIGN BASES

<table>
<tr><th>Eductor Station</th><th>Compressed Air U-Tube
(in force main)</th><th>Aspirated Air U-Tube
(in force main)</th><th>Aspirated Air U-Tube
(in gravity main)</th></tr>
<tr>
<td>Casing is 20 ft deep

Construction cost is $13,000 for 1500 gpm unit

Exit D.O. roughly calculated to be 3.3 mgl

Air compressor delivers 40 v/o air at 59 ft of total head</td>
<td>Construction cost is $11,800 for 300 gpm unit 30 ft deep, $12,800 for 300 gpm unit 50 ft deep, and $11,300 for 300 gpm unit 20 ft deep

Design points are as follows:
<table>
<tr><th>Depth (ft)</th><th>Air Volume Fraction at 1 atm</th><th>Exit D.O. (mg/l)</th><th>Extra Head on Pump (ft)</th></tr>
<tr><td>20</td><td>0.045</td><td>2.0</td><td>2.2</td></tr>
<tr><td>30</td><td>0.12</td><td>4.0</td><td>4.5</td></tr>
<tr><td>50</td><td>0.24</td><td>7.0</td><td>10.0</td></tr>
</table>
</td>
<td>Construction cost is $20,300 for 1800 gpm unit 30 ft deep and $22,700 for 1800 gpm unit 50 ft deep

Dynamic ΔH = 4.0 ft
Static ΔH = 7.0 ft
Total ΔH = 11.0 ft

Exit D.O. (30 ft) = 4.24 mg/l
Exit D.O. (50 ft) = 5.40 mg/l</td>
<td>Construction cost of 1800 gpm unit is same as for aspirated air U-tube

Design points are as follows:
<table>
<tr><th>Depth (ft)</th><th>Total ΔH (ft)</th><th>Exit D.O. (mg/l)</th></tr>
<tr><td>30</td><td>4</td><td>2.6</td></tr>
<tr><td>30</td><td>11</td><td>4.6</td></tr>
<tr><td>50</td><td>4</td><td>2.7</td></tr>
<tr><td>50</td><td>11</td><td>5.6</td></tr>
</table>
</td>
</tr>
</table>

Yearly cost elements for each of the systems are amortized capital, maintenance, power, and operating labor plus materials. No land, administrative, or overhead costs were considered. Construction costs were based on actual bid prices. Construction costs for 2085 gpm units were determined from a plant capacity scale equation, viz.

$$P_B = P_A \left(\frac{r_B}{r_A}\right)^{0.4}$$

where P_B, P_A = construction costs of plants B and A, respectively,

and r_B, r_A = production rates (through-put) of plants B and A, respectively.

The 0.4 scale factor, suggested for plants of small capacities,[22] appears to be valid. When the construction costs of 300 gpm compressed air U-tubes were scaled to 2085 gpm, the prices were only slightly greater than those for 1500 gpm aspirated air U-tubes scaled to 2085 gpm. It is reasonable to expect the compressed air units to cost somewhat more because of the associated blower and air ducts.

The construction bid prices were assumed to include contractor's fee, contractor's overhead, and contingency. Fixed capital costs were taken as 110 percent of the construction bid prices (10 percent engineering fee). Capital costs were amortized at 4.5 percent over 25 years. Power was assumed to cost 1¢/kw-hr. Operating labor was assumed to be $100/year. The annual maintenance cost was assumed to be 1 to 3 percent of the construction bid price.

Economic Comparison of In-Situ Aerators

A summary of costs for all systems at selected values of exit D.O. is given in Table 13. The "differential head" column refers to the net increase (or decrease) in system head due to pressure loss (or recovery) through the aerator. Costs are given, assuming that the differential head is free or assuming that the additional power costs required to pump the differential head must be paid.

Costs generally range from 4 to 10 cents per pound. Costs for gravity and force main aspirated-air U-tubes are essentially the same for comparable depths and differential head. The modest cost difference is due to slightly increased mass transfer in a gravity flow U-tube. A general trend for all U-tubes is lower cost at higher differential head, over the range of values investigated.

The following conclusions can be drawn from this comparison of the costs of in-situ aeration of sewer waste water. Given an existing sewer system, the cheapest mode for aeration is an aspirated-air or compressed-air U-tube at the end of a force main. In the case of new system construction, an aspirated-air U-tube in a gravity line will

TABLE 13

COST COMPARISON FOR IN-SITU AERATION OF SEWER WASTE WATER

System	Casing Depths (ft)	Exit D.O. (mg/1)	Differential Head (ft)	Cost (Cents/lb. D.O.)				
				Amortized Capital	Maintenance and Operating Labor	Power[(b)]	Total	Total Including ΔH Cost
Eductor station	20	2.2	-3.0[(a)]	3.8	1.9	3.9	10.3	9.6
Compressed-air U-tube in force main	20	2.0	+2.2	11.0	5.0	0.9	16.1	16.9
	30	4.0	+4.5	5.4	2.5	0.9	8.0	8.8
	50	7.0	+10.0	3.3	1.5	1.2	5.0	6.0
Aspirated-air U-tube at end of force main	30	4.2	+11.0	4.3	0.9	1.8	5.2	7.0
	50	5.4	+11.0	3.8	0.7	1.4	4.5	5.9
Aspirated-air U-tube in gravity flow main	30	2.6	+4.0	7.3	1.4	1.1	8.7	9.8
	30	4.6	+11.0	3.9	0.8	1.7	4.7	6.4
	50	2.7	+4.0	7.9	1.5	1.0	9.4	10.4
	50	5.6	+11.0	3.6	0.7	1.4	4.3	5.7

(a) assumes eductor yields 3 ft water lift

(b) includes both air compressor power (where applicable) and cost or credit for differential head, ΔH be the least expensive system. An aspirated-air U-tube in a gravity line would be the least expensive, in an existing system, but it is unlikely that sufficient head would be available.

NOMENCLATURE

a = air-water interfacial area per unit total volume of water-air mixture

A = area

b = half-angle of venturi conical diffuser

C = concentration of dissolved gas

C_s = saturation concentration of dissolved gas

D = diameter; dissolved oxygen concentration deficit (C_s-C)

E = aspirator contraction area ratio (cross-sectional area of pipe divided by minimum flow cross-sectional area in aspirator)

f* = friction factor for gas lifts (see equation set 11)

F = Change in pressure per unit length (includes both static head and friction losses)

h = step-size, distance along tube for one calculation step

ΔH = differential head

K = overall mass transfer coefficient including interfacial area ($K = K_L a$)

K_L = overall mass transfer coefficient (dimensions are length/time)

L = U-tube depth, measured from top of down-leg to bottom of return bend

M = molecular weight

n = number of moles

n_i = number of moles of "inert" vapors (i.e., air components which are not oxygen or nitrogen)

N = performance rating of aerators (lb oxygen transferred/hp-hr)

p = absolute pressure

p_o = ambient absolute pressure

p_v = vapor pressure of water at prevailing temperature

Q = volumetric flow rate

Q_s = air flow relative to water flow

r = plant production rate

R = ratio of venturi permanent pressure drop to pressure decrease between entrance and the throat: $(p_3 - p_5)/(p_3 - p_4)$

Re = Reynolds Number
t = time
Δt_a = average time for air bubble to move the distance h
t_w = average time for water to move the distance h
T = temperature
u = velocity
u_s = slip velocity = water velocity minus air bubble velocity
u_w = superficial water velocity (i.e., velocity with which the water in an air-water mixture would flow, at the specified volumetric water flow rate, if the air were not present)
V = volume
x = air-water interfacial area per unit volume of air
y = ratio of air volume to liquid volume
y_o = y before mass transfer begins

Greek

α = ratio of mass transfer coefficient for waste water of interest to mass transfer coefficient of "tap water"
μ = viscosity
ρ = density

Subscripts

a = air
d = down-leg of U-tube
m = two-phase mixture of water and air
p = solid particle
s = saturated conditions (e.g., C_s); slip between water and air (for u_s and Q_s)
t = total
T = evaluated at temperature T
u = up-leg of U-tube
w = water
20 = evaluated at a temperature of 20°C (68°F)

Superscripts

o = evaluated at standard conditions (1 atm, 68°F unless otherwise specified)
' = nitrogen, rather than oxygen transfer
- = mean value

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APPENDIX A

U-TUBE EXPERIMENTAL DATA WITH CENTER-PLUG ASPIRATOR

Table A-1 summarizes the data taken in the 94 U-tube experimental tests made with the center-plug aspirator. Mass transfer coefficients were not calculated from these data as they were for the tests with the venturi aspirator (see Appendix B). The air flow rate measurements were not as accurate for these early runs as they were in the later tests (after Run 94); therefore, the reported air-to-water volume ratios and amounts of oxygen supplied may have errors as large as ± 15 percent. The differential head reported below has been corrected for the pressure loss due to curvature in the hose between the U-tube exit and the vacuum break tee. Since only two D.O. meters were available at the beginning of the experimental effort, only inlet and outlet D.O.'s were recorded. There are no entries in Table A-1 for some run numbers. These were runs in which equipment was merely being checked or for which no data were recorded.

TABLE A-1

EXPERIMENTAL DATA FOR U-TUBE TESTS WITH CENTER-PLUG ASPIRATOR

Run Number	U-tube Depth (ft)	Water Velocity (ft/sec)	Temperature (°F)	Air-to-Water Volume Ratio x 100 At 13.8 psia, 68°F	O_2 Supplied to Water (mg/1)	D.O. in Influent (mg/1)	D.O. in Effluent (mg/1)	Differential Head Across U-tube (ft H_2O)
1	37	0.8	86.5	-	-	2.26	2.32	2.4
2	37	0.7	82.8	-	-	1.54	4.02	4.9
3	37	0.8	86	-	-	1.56	3.61	2.4
4	37	0.8	87	-	-	1.55	2.74	0.2
5	37	1.5	87.5	-	-	1.61	3.29	0.5
6	37	1.2	79.5	2.58	6.79	2.95	6.58	2.6
8	37	1.1	87.5	1.95	5.13	2.45	5.95	3.1
10	37	0.9	79	.51	1.34	2.81	4.94	3.1
13	37	1.6	100	1.17	3.08	2.42	4.33	4.2
14	37	1.5	107	1.84	4.84	2.38	4.51	4.2
15	37	1.3	107	2.11	5.55	1.22	4.27	4.2
16	37	1.4	95	2.05	5.40	1.52	5.16	2.5
18	37	2.4	90	10.51	27.70	0.97	6.06	3.6
19	37	2.7	92	7.15	18.80	0.95	5.08	3.3
20	37	2.9	94	4.62	12.15	0.93	3.99	3.3
21	37	2.2	105	.86	2.26	1.23	2.28	1.9
23	37	3.1	105	4.36	11.48	2.04	3.70	4.6
24	37	2.8	104	6.90	18.15	1.98	4.71	4.6
25	37	2.7	102	8.88	23.35	2.32	5.52	4.6
26	45	1.4	80.5	0	0			3.7
27	45	2.4	81	0	0			4.2
28	45	2.8	84	0	0			4.2
29	45	3.9	84	0	0			4.2
30	45	3.3	84	0	0			4.2
31	45	1.9	85	0	0			3.9

TABLE A-1 (CONT'D)

Run Number	U-tube Depth (ft)	Water Velocity (ft/sec)	Temperature (°F)	Air-to-Water Volume Ratio x 100 At 13.8 psia, 68°F	O_2 Supplied to Water (mg/l)	D.O. in Influent (mg/l)	D.O. in Effluent (mg/l)	Differential Head Across U-tube (ft H_2O)
33	45	2.8	75	2.88	7.58	1.34	3.40	4.2
34	45	2.9	74	3.68	9.68	1.52	3.91	4.2
35	45	3.3	75	2.96	7.79	1.34	3.40	4.2
36	45	3.7	75	2.92	7.68	1.27	3.48	4.2
37	45	3.4	73	4.86	12.79	1.37	4.53	4.2
38	45	2.9	73	5.96	15.69	1.46	5.10	4.2
39	45	2.4	73	6.56	17.25	1.70	5.66	3.7
40	45	2.4	72	5.32	14.00	2.12	5.47	4.2
41	45	1.8	61	3.28	8.63	1.84	5.52	4.2
42	45	2.3	63	4.46	11.72	1.98	5.30	4.2
43	45	2.9	64	6.28	16.52	1.78	5.87	4.2
44	45	3.3	65	5.20	13.68	1.67	5.10	4.2
45	45	3.8	70	1.90	5.00	1.83	3.16	4.2
46	45	3.8	70	2.69	17.08	1.92	3.50	4.2
47	45	3.7	70	3.67	9.65	1.92	3.91	4.2
48	45	3.3	70	2.15	5.66	2.08	3.58	4.2
49	45	2.8	70	6.28	16.51	1.92	5.00	4.2
50	45	3.3	71	2.16	5.68	1.07	2.72	4.2
51	45	1.4	69	1.33	3.50	1.68	5.21	4.2
52	45	1.9	70	2.92	7.68	1.67	5.00	4.2
53	45	1.8	70	5.61	14.75	1.83	6.42	3.9
54	45	2.4	70	5.93	15.60	1.83	6.08	4.2
55	45	1.9	70	7.20	18.94	1.92	6.83	3.9
56	45	2.9	67	.98	2.58	1.81	3.52	4.2
57	45	3.7	67	.76	2.00	1.72	3.10	4.2
58	45	1.9	67	.51	1.34	1.98	3.18	4.2
59	45	1.9	65	5.25	13.81	1.85	6.16	3.9
60	45	2.8	66	5.36	14.10	2.09	5.74	4.2

TABLE A-1 (CONT'D)

Run Number	U-tube Depth (ft)	Water Velocity (ft/sec)	Temperature (°F)	Air-to-Water Volume Ratio x 100 At 13.8 psia, 68°F	O_2 Supplied to Water (mg/1)	D.O. in Influent (mg/1)	D.O. in Effluent (mg/1)	Differential Head Across U-tube (ft H_2O)
61	45	3.3	70	4.27	11.23	1.58	4.33	4.2
62	45	2.9	70	5.41	14.23	1.58	5.25	4.2
63	45	1.4	71	5.85	15.39	1.32	3.05	4.2
64	45	2.4	70	5.73	15.07	1.58	5.50	4.2
65	45	2.9	70	7.72	20.30	1.67	6.00	5.0
66	45	2.9	69	8.65	22.75	1.77	6.48	5.0
67	45	3.3	66	6.30	16.57	1.74	5.91	4.7
68	45	3.4	68	6.19	16.29	1.70	5.88	4.6
69	45	3.3	69	6.72	17.68	1.60	5.97	4.6
70	45	2.3	70	8.73	22.95	1.42	6.75	5.0
71	45	2.5	70	7.90	20.80	1.50	6.58	5.2
72	45	1.9	71	9.15	24.06	1.48	7.18	5.2
73	45	3.3		0	0			5.4
74	45	2.9		0	0			5.8
75	45	2.5		0	0			6.3
76	45	1.8		0	0			6.8
77	45	2.9		0	0			4.6
78	45	2.4		0	0			3.1
79	45	1.8		0	0			2.2
80	45	2.3		0	0			3.2
81	45	1.8		0	0			3.1
82	45	2.2		0	0			5.1
83	45	1.5		0	0			5.1
84	45	1.1		0	0			2.2
85	45	2.8		0	0			3.1
86	45	3.1		0	0			3.7
87	45	3.3		0	0			4.5
88	45	2.4		0	0			2.3
89	45	2.6		0	0			2,4

TABLE A-1 (CONT'D)

Run Number	U-tube Depth (ft)	Water Velocity (ft/sec)	Temperature (°F)	Air-to-Water Volume Ratio x 100 At 13.8 psia, 68°F	O_2 Supplied to Water (mg/1)	D.O. in Influent (mg/1)	D.O. in Effluent (mg/1)	Differential Head Across U-tube (ft H_2O)
90	45	3.0		0	0			3.1
91	45	3.4		0	0			4.2
92	45	3.4		0	0			3.4
93	45	2.9		0	0			2.6
94	45	2.5		0	0			2.0

APPENDIX B

U-TUBE EXPERIMENTAL DATA WITH VENTURI ASPIRATOR

This appendix contains experimental data, plus other qualities calculated with the data reduction computer program, for the U-tube experimental tests made with a venturi aspirator. The information is arranged into three tables, each of which presents results in order of increasing run number. An outline of the contents of the tables and identification of which values are experimental ones are given in the following paragraphs.

Table B-1 contains experimental data for those tests made without air flow (water flow only). The true exit head values include a correction for the curvature and extra length of the outlet hose.

Table B-2 contains measured values of U-tube depth (distance from the entrance of the down-leg to the bottom of the return bend), water flow rate, air-to-water volume ratio (A/W on the print-outs) expressed at 13.8 psia and 68°F (typical conditions at the experimental site), ambient pressure, and water temperature. The amount of oxygen supplied, expressed as mg/l, is equal to 2.63 times the air-to-water volume ratio expressed at 13.8 psia and 68°F. The remaining four columns in Table B-2 contain calculated values of superficial water velocity (the velocity of water in the pipe at the measured volumetric flow rate if no air were present), true overall pressure drop through the system (DELTA H), and values of the mass transfer coefficient K_L, at the water temperature and at 68°F (20°C).

Table B-3 summarizes values of dissolved oxygen concentration, dissolved nitrogen concentration, and head loss relative to the inlet tank water level--with values of each quantity for several stations in the U-tube system. The entrance and exit D.O. concentrations ENTR and EXIT(EXP), are experimental values in all cases. The D.O. concentrations at the exit of the venturi aspirator are experimental values for runs 139-167 and 180-219, inclusive. The D.O. values at the exit of the return bend for runs 225-252 are experimental data. The entries for D.O. concentrations at the platform (i.e., the junction between the straight section of up-leg and the flexible exit hose) are experimental values for runs 273-318. The EXIT (CALC) column gives values of D.O. calculated at the exit of the flexible hose; these were printed primarily as a check (by comparing with the EXIT (EXP) column) that the program had successfully converged. The TRUE EXIT columns for D.O., D.N., and head loss gives the calculated values at the exit of a U-tube which has a straight pipe up-leg rather than partly straight pipe plus a flexible outlet hose as did the experimental system. The TRUE EXIT HEAD values are identical to the DELTA H values of Table B-2. These true exit values should be used in applying the experimental results to other applications. The values of D.N. are all estimated ones, based on the assumptions discussed in the Data Reduction Program section. The head loss columns for the venturi exit and U-bend entrance contain experimental data exclusively. The column for head loss at U-bend exit contains entirely calculated values. The values for head loss at the platform are experimental data for runs 332-410.

The quantity, weight of oxygen transferred per unit of power expended (N), is a widely used figure-of-merit. However, it can lead to very misleading conclusions if used to compare different types of aeration systems, since power cost is only one component of the total aeration cost. Values of N at standard conditions (tap water at 1 atm, 20° C, and zero inlet D.O.) were calculated for experimental data contained in this appendix and were found to range from less than 1 to nearly 7 lb oxygen/hp-hr. Ranges of N values for each of the five U-tube depths are given below.

U-Tube Depth (ft)	Range of N Values (at standard conditions) from Experimental Data (lb oxygen/hp-hr)
45	1.4 to 5.1
37	1.0 to 6.7
28	0.7 to 6.0
19	1.1 to 4.0
9	0.5 to 1.8

It should be remembered that the ranges of water velocities and air-to-water ratios were not identical for the five U-tube depths; therefore, some differences between the ranges of N for different depths could result from this. In general, the experimental N values seem to increase with increasing U-tube depth, decreasing water velocity and increasing air-to-water ratio. If an aspirated-air U-tube were installed where the required head is available naturally, the value of N would literally be infinite.

TABLE B-1

EXPERIMENTAL DATA FOR U-TUBE TESTS WITH VENTURI ASPIRATOR, NO AIR FLOW

Run Number	U-tube Depth (ft)	Supf. Water Velocity (ft/sec)	Water Flowrate (gpm)	Head Relative to Inlet (ft)		
				Venturi Exit	Bend Entrance	True Exit
95	45.4	2.1	22.1	0.7	1.2	1.8
96	45.4	1.0	10.3	0.2	0.3	0.9
97	45.4	1.9	19.9	0.7	1.0	1.3
98	45.4	2.5	25.8	1.0	1.7	2.2
99	45.4	2.6	27.6	1.3	1.9	2.6
100	45.4	3.0	30.9	1.4	2.3	3.1
101	45.4	3.0	31.9	1.7	2.6	3.5
102	45.4	3.4	35.0	1.8	2.9	4.0
103	45.4	3.5	37.0	2.0	3.2	4.4
104	45.4	3.8	39.3	2.2	3.4	4.8
105	45.4	2.9	30.1	1.4	2.4	3.1
168	18.8	1.8	18.9	0.6	0.7	0.8
169	18.8	2.0	20.6	0.7	0.9	1.0
170	18.8	2.2	22.2	0.9	1.0	1.2
171	18.8	2.4	25.2	1.0	1.3	1.4
172	18.8	2.5	26.5	1.2	1.4	1.6
173	18.8	2.7	28.1	1.3	1.7	1.8
174	18.8	2.8	29.4	1.4	1.8	2.0
175	18.8	3.0	31.2	1.6	1.9	2.2
176	18.8	3.2	33.1	1.7	2.1	2.3
177	18.8	3.4	35.2	1.8	2.2	2.5
178	18.8	3.5	36.2	1.9	2.4	2.7
179	18.8	3.6	37.2	2.0	2.5	2.9
220	8.9	2.7	28.0	1.3	1.4	1.6
221	8.9	2.3	24.2	0.9	1.0	1.2
222	8.9	1.9	20.1	0.7	0.7	0.8
223	8.9	1.4	14.9	0.4	0.4	0.4
224	8.9	3.0	31.4	1.5	1.6	2.1
264	27.9	1.6	16.7	0.5	0.7	0.9
265	27.9	2.0	20.4	0.8	1.0	1.3
266	27.9	1.8	18.8	0.7	0.9	1.1
267	27.9	2.1	21.9	0.9	1.2	1.5
268	27.9	2.3	23.7	1.0	1.3	1.7
269	27.9	2.4	25.3	1.1	1.4	1.9

TABLE B-1 (CONT'D)

Run Number	U-tube Depth (ft)	Supf. Water Velocity (ft/sec)	Water Flowrate (gpm)	Head Relative to Inlet (ft)		
				Venturi Exit	Bend Entrance	True Exit
270	27.9	2.5	25.8	1.2	1.6	2.0
271	27.9	2.8	28.8	1.4	1.9	2.3
272	27.9	3.0	31.8	1.7	2.3	2.8
326	36.5	1.6	16.7	0.5	0.7	0.8
327	36.5	1.9	20.0	0.7	1.0	1.3
328	36.5	2.2	23.0	0.9	1.4	1.8
329	36.5	2.4	25.6	1.0	1.6	2.2
330	36.5	2.7	27.8	1.3	2.0	2.4
331	36.5	3.0	31.2	1.5	2.3	3.0
403	36.5	1.6	16.9	0.5	0.7	0.8
404	36.5	2.0	20.4	0.7	1.0	1.3
405	36.5	2.2	23.3	0.9	1.3	1.7
406	36.5	2.4	25.5	1.0	1.6	2.2
407	36.5	2.7	28.4	1.3	2.0	2.7
408	36.5	2.9	30.3	1.5	2.2	3.1
409	36.5	3.1	32.4	1.7	2.5	3.6
410	36.5	3.4	35.2	1.9	2.7	4.0

TABLE B-2. U-TUBE EXPERIMENTAL DATA WITH CALCULATED MASS TRANSFER COEFFICIENTS

RUN NO.	DEPTH (FT)	S.W.VEL (FT/SEC)	QW (GPM)	A/W (V/O)	P.AMB (FTH2O)	TW (F)	DELTA H (FEET)	KL(TW) (FT/SEC)	KL(20 C) (FT/SEC)
106	45.42	1.93	20.2	2.10	31.9	71.	2.61	0.935E-03	0.899E-03
107	45.42	2.32	24.3	3.25	31.9	72.	3.67	0.889E-03	0.844E-03
108	45.42	1.91	20.0	4.10	31.9	72.	2.96	0.793E-03	0.752E-03
109	45.42	2.40	25.1	5.50	31.9	72.	4.19	0.788E-03	0.747E-03
110	45.42	1.90	19.9	7.67	31.9	72.	3.41	0.644E-03	0.611E-03
111	45.42	1.90	19.9	8.90	31.9	74.	3.67	0.798E-03	0.738E-03
112	45.42	2.90	30.3	4.36	31.9	75.	6.02	0.106E-02	0.969E-03
113	45.42	2.40	25.1	7.10	31.9	74.	4.73	0.858E-03	0.793E-03
114	45.42	2.90	30.3	2.10	31.9	74.	5.46	0.278E-02	0.256E-02
115	45.42	2.80	29.3	4.82	31.9	75.	5.87	0.135E-02	0.123E-02
116	45.42	1.83	19.1	10.34	31.9	76.	3.54	0.987E-03	0.888E-03
117	45.42	2.40	25.1	6.33	31.8	74.	4.94	0.910E-03	0.841E-03
118	45.42	2.90	30.3	3.27	31.8	75.	5.65	0.144E-02	0.131E-02
119	45.42	2.90	30.3	4.65	31.8	76.	6.11	0.129E-02	0.116E-02
120	45.42	2.41	25.2	3.25	31.8	68.	3.85	0.102E-02	0.102E-02
121	45.42	1.91	20.0	5.05	31.8	70.	3.06	0.846E-03	0.824E-03
122	45.42	2.45	25.6	0.82	31.9	65.	3.54	0.262E-02	0.273E-02
123	45.42	2.41	25.2	2.36	31.9	67.	4.34	0.141E-02	0.143E-02
124	45.42	2.92	30.5	2.90	31.9	68.	5.85	0.130E-02	0.130E-02
125	45.42	2.90	30.3	4.26	31.9	69.	6.19	0.102E-02	0.101E-02
126	45.42	2.32	24.3	7.06	31.9	70.	4.67	0.894E-03	0.870E-03
127	45.42	1.87	19.6	9.57	31.9	70.	3.62	0.760E-03	0.740E-03
128	45.42	1.40	14.6	1.25	31.9	71.	1.35	0.650E-02	0.625E-02
129	45.42	2.86	29.9	1.40	31.9	73.	4.89	0.215E-02	0.201E-02
130	45.42	2.37	24.8	0.84	32.0	73.	3.16	0.280E-02	0.263E-02
131	45.42	2.90	30.3	1.44	32.0	74.	4.92	0.225E-02	0.208E-02
132	45.42	2.41	25.2	4.51	32.0	74.	4.06	0.973E-03	0.899E-03
133	45.42	1.95	20.4	6.60	32.0	76.	3.47	0.902E-03	0.812E-03
134	45.42	1.90	19.9	2.10	31.9	76.	2.49	0.188E-02	0.169E-02
135	45.42	2.83	29.6	3.90	31.9	76.	5.80	0.128E-02	0.115E-02
136	45.42	2.40	25.1	6.70	31.9	75.	5.11	0.100E-02	0.916E-03
137	45.42	2.00	20.9	9.40	31.9	75.	4.15	0.817E-03	0.745E-03
138	45.42	2.83	29.6	4.50	31.9	76.	6.07	0.118E-02	0.106E-02
139	45.42	2.40	25.1	0.90	32.0	75.	3.38	0.314E-02	0.287E-02

RUN NO.	DEPTH (FT)	S.W.VEL (FT/SEC)	QW (GPM)	A/W (V/D)	P.AMB (FTH2O)	TW (F)	DELTA H (FEET)	KL(TW) (FT/SEC)	KL(20 C) (FT/SEC)
140	45.42	2.40	25.1	2.70	32.0	74.	3.67	0.131E-02	0.121E-02
141	45.42	2.40	25.1	5.22	32.0	74.	4.23	0.917E-03	0.847E-03
142	45.42	2.35	24.6	6.49	32.0	75.	4.62	0.892E-03	0.814E-03
143	45.42	2.34	24.5	7.20	32.0	74.	4.87	0.913E-03	0.844E-03
144	45.42	2.94	30.8	3.80	32.0	74.	6.18	0.111E-02	0.103E-02
145	45.42	2.80	29.3	5.20	32.0	74.	6.10	0.111E-02	0.103E-02
147	45.42	2.84	29.7	2.60	31.9	80.	4.90	0.165E-02	0.141E-02
148	45.42	2.90	30.3	3.40	31.9	79.	5.58	0.140E-02	0.121E-02
149	45.42	1.90	19.9	10.10	31.9	78.	3.74	0.771E-03	0.676E-03
150	45.42	1.94	20.3	6.90	31.9	78.	3.60	0.100E-02	0.880E-03
151	45.42	1.86	19.5	3.85	31.9	77.	2.98	0.138E-02	0.122E-02
152	45.42	1.92	20.1	1.70	31.9	75.	2.74	0.932E-02	0.850E-02
153	45.42	1.92	20.1	1.40	31.9	58.	2.46	0.222E-02	0.254E-02
154	45.42	1.86	19.5	2.14	31.9	59.	2.45	0.196E-02	0.220E-02
155	45.42	1.92	20.1	3.60	31.9	60.	2.97	0.124E-02	0.137E-02
156	45.42	1.85	19.4	7.70	31.9	63.	3.33	0.764E-03	0.849E-03
157	45.42	1.87	19.6	9.18	31.9	61.	3.65	0.739E-03	0.810E-03
158	45.42	2.33	24.4	6.20	31.9	62.	4.46	0.901E-03	0.975E-03
159	45.42	2.43	25.4	3.90	31.9	63.	4.13	0.120E-02	0.128E-02
160	45.42	2.33	24.4	2.80	31.9	63.	3.63	0.148E-02	0.158E-02
161	45.42	2.36	24.7	1.30	31.9	63.	3.35	0.312E-02	0.333E-02
162	45.42	2.37	24.8	7.00	31.9	63.	4.83	0.908E-03	0.970E-03
163	45.42	2.88	30.1	3.78	31.9	64.	6.07	0.119E-02	0.126E-02
164	45.42	2.90	30.3	3.80	31.9	64.	6.09	0.132E-02	0.139E-02
165	45.42	2.90	30.3	2.40	31.9	64.	5.49	0.174E-02	0.183E-02

RUN NO.	DEPTH (FT)	S.W.VEL (FT/SEC)	QW (GPM)	A/W (V/O)	P.AMB (FTH2O)	TJ (F)	DELTA H (FEET)	KL(TW) (FT/SEC)	KL(20 C) (FT/SEC)
180	18.83	2.34	24.5	1.68	32.0	61.	2.32	0.200E-02	0.220E-02
181	18.83	1.87	19.6	3.63	32.0	63.	1.88	0.147E-02	0.157E-02
182	18.83	1.94	20.3	5.19	32.0	64.	2.15	0.102E-02	0.108E-02
183	18.83	2.31	24.2	2.61	32.0	65.	2.61	0.163E-02	0.170E-02
185	18.83	2.83	29.6	1.76	32.0	66.	3.32	0.286E-02	0.294E-02
186	18.83	2.44	25.5	4.37	32.0	67.	2.88	0.147E-02	0.149E-02
187	18.83	1.88	19.7	6.82	32.0	67.	2.42	0.126E-02	0.128E-02
188	18.83	2.45	25.6	5.01	32.0	68.	3.22	0.143E-02	0.143E-02
189	18.83	1.91	20.0	8.97	32.0	68.	2.73	0.113E-02	0.113E-02
190	18.83	2.90	30.3	2.02	32.0	68.	4.01	0.279E-02	0.279E-02
191	18.83	2.85	29.8	3.47	32.0	68.	3.99	0.187E-02	0.187E-02
192	18.83	2.38	24.9	7.02	32.0	69.	3.45	0.144E-02	0.142E-02
193	18.83	1.90	19.9	8.81	32.0	69.	2.64	0.117E-02	0.115E-02
194	18.83	2.37	24.9	7.23	32.0	70.	3.93	0.146E-02	0.142E-02
195	18.83	2.93	30.2	4.11	32.0	69.	4.50	0.189E-02	0.186E-02
196	18.83	2.89	30.2	4.78	32.0	69.	4.83	0.174E-02	0.172E-02
197	18.83	2.30	24.1	7.71	32.0	69.	3.91	0.141E-02	0.140E-02
198	18.83	2.34	24.5	8.22	31.9	71.	4.19	0.132E-02	0.127E-02
199	18.83	2.91	30.4	5.58	31.9	70.	5.52	0.123E-02	0.120E-02
200	18.83	2.43	25.4	7.53	31.9	70.	4.49	0.125E-02	0.122E-02
201	18.83	2.80	29.3	6.00	31.9	71.	5.23	0.133E-02	0.128E-02
203	18.83	2.37	24.8	1.09	31.9	70.	2.40	0.547E-02	0.533E-02
204	18.83	1.90	19.9	2.71	32.0	62.	1.99	0.166E-02	0.180E-02
205	18.83	1.91	20.0	5.44	32.0	63.	2.11	0.926E-03	0.989E-03
206	18.83	1.94	20.3	6.81	32.0	65.	2.39	0.988E-03	0.103E-02
207	18.83	1.92	20.1	8.79	32.0	65.	2.75	0.904E-03	0.941E-03
208	18.83	1.90	19.9	9.98	32.0	66.	3.10	0.860E-03	0.883E-03
209	18.83	2.35	24.6	6.67	32.0	67.	3.57	0.993E-03	0.101E-02
210	18.83	2.41	25.2	6.77	32.0	66.	3.99	0.111E-02	0.114E-02
211	18.83	2.39	25.0	8.60	32.0	67.	4.33	0.109E-02	0.110E-02
212	18.83	2.38	24.9	4.08	32.0	67.	2.78	0.131E-02	0.133E-02
213	18.83	2.37	24.8	1.06	32.0	67.	2.40	0.517E-02	0.524E-02
215	18.83	2.90	30.3	1.42	32.0	67.	3.44	0.322E-02	0.326E-02
216	18.83	2.87	30.0	2.63	32.0	68.	4.08	0.196E-02	0.196E-02

RUN NO.	DEPTH (FT)	S.W.VEL (FT/SEC)	QW (GPM)	A/W (V/O)	P.AMB (FTH2O)	TW (F)	DELTA H (FEET)	KL(TW) (FT/SEC)	KL(20 C) (FT/SEC)
217	18.83	2.90	30.3	4.12	32.0	67.	4.65	0.141E-02	0.143E-02
218	18.83	2.89	30.1	5.11	32.0	68.	5.20	0.124E-02	0.124E-02
219	18.83	2.91	30.4	5.33	32.0	68.	5.44	0.126E-02	0.126E-02
225	8.92	2.35	24.6	2.21	31.8	68.	4.40	0.230E-02	0.230E-02
226	8.92	1.97	19.6	3.15	31.8	69.	3.79	0.233E-02	0.230E-02
227	8.92	1.87	19.6	3.80	31.8	69.	3.86	0.223E-02	0.220E-02
228	8.92	2.44	25.5	2.56	31.8	68.	4.75	0.295E-02	0.295E-02
229	8.92	2.41	25.2	5.51	31.8	68.	5.52	0.176E-02	0.176E-02
230	8.92	1.93	20.2	6.47	31.8	68.	4.35	0.182E-02	0.182E-02
231	8.92	1.94	20.3	9.30	31.8	69.	4.74	0.128E-02	0.127E-02
232	8.92	2.32	24.3	8.03	31.8	69.	5.65	0.146E-02	0.145E-02
233	8.92	2.39	25.0	10.64	31.8	68.	6.83	0.119E-02	0.119E-02
234	8.92	1.86	19.5	20.35	31.8	68.	5.22	0.986E-03	0.986E-03
235	8.92	2.86	29.9	0.63	31.9	65.	4.85	0.360E-02	0.375E-02
236	8.92	2.83	29.6	2.71	31.9	66.	5.39	0.260E-02	0.267E-02
237	8.92	2.84	29.7	4.35	31.9	67.	6.02	0.187E-02	0.190E-02
238	8.92	2.93	30.6	4.71	31.9	68.	6.73	0.123E-02	0.123E-02
239	8.92	2.86	29.9	5.87	31.9	68.	7.13	0.132E-02	0.132E-02
240	8.92	2.88	30.1	6.44	31.9	69.	7.73	0.127E-02	0.125E-02
241	8.92	2.92	30.5	7.16	31.9	69.	8.23	0.133E-02	0.131E-02
242	8.92	2.37	24.8	1.95	31.8	69.	4.41	0.277E-02	0.273E-02
243	8.92	1.90	19.9	3.43	31.8	70.	3.93	0.214E-02	0.209E-02
244	8.92	2.93	30.6	1.27	31.8	70.	5.18	0.363E-02	0.354E-02
245	8.92	2.37	24.8	4.20	31.8	71.	4.61	0.258E-02	0.248E-02
246	8.92	1.90	19.9	5.77	31.8	71.	4.07	0.183E-02	0.176E-02
247	8.92	2.94	30.8	2.63	31.8	72.	5.91	0.223E-02	0.211E-02
248	8.92	2.36	24.7	6.68	31.8	72.	5.71	0.142E-02	0.135E-02
249	8.92	1.87	19.6	8.45	31.8	72.	4.45	0.164E-02	0.156E-02
250	8.92	2.84	29.7	5.04	31.8	73.	6.60	0.181E-02	0.170E-02
251	8.92	2.40	25.1	8.63	31.8	73.	6.53	0.145E-02	0.136E-02
252	8.92	1.96	20.5	13.33	31.8	73.	4.84	0.137E-02	0.129E-02
253	8.92	2.33	24.4	2.16	32.0	68.	4.39	0.208E-02	0.208E-02

RUN NO.	DEPTH (FT)	S.W.VEL (FT/SEC)	QW (GPM)	A/V (V/O)	P.AMB (FTH2O)	TW (F)	DELTA H (FEET)	KL(TW) (FT/SEC)	KL(20 C) (FT/SEC)
254	8.92	1.93	20.2	3.03	32.0	68.	3.96	0.217E-02	0.217E-02
255	8.92	2.43	25.4	5.50	32.0	69.	5.52	0.130E-02	0.128E-02
256	8.92	2.94	29.7	2.29	32.0	70.	5.60	0.245E-02	0.239E-02
257	8.92	1.87	19.6	6.68	32.0	70.	4.16	0.153E-02	0.149E-02
258	8.92	2.43	25.4	8.47	32.0	70.	6.54	0.131E-02	0.127E-02
259	8.92	2.94	29.7	4.88	32.0	70.	6.75	0.190E-02	0.185E-02
260	8.92	1.94	20.3	10.94	32.0	71.	4.94	0.146E-02	0.140E-02
261	8.92	2.35	24.6	10.04	32.0	71.	6.84	0.155E-02	0.149E-02
262	8.92	2.89	30.1	6.05	32.0	71.	7.89	0.163E-02	0.156E-02
263	8.92	1.83	19.7	12.98	32.0	70.	4.58	0.116E-02	0.113E-02
273	27.92	1.86	19.7	4.08	32.0	64.	2.30	0.115E-02	0.121E-02
274	27.92	2.35	24.6	2.15	32.0	64.	2.74	0.140E-02	0.147E-02
275	27.92	2.83	29.6	1.72	32.0	63.	3.74	0.150E-02	0.160E-02
276	27.92	2.36	24.7	2.78	32.0	63.	3.54	0.250E-02	0.268E-02
277	27.92	1.94	20.3	7.10	32.0	64.	2.80	0.809E-03	0.852E-03
278	27.92	1.91	20.0	10.31	32.0	64.	3.22	0.756E-03	0.797E-03
279	27.92	2.36	24.7	6.23	32.0	64.	3.95	0.101E-02	0.106E-02
280	27.92	2.88	30.1	3.21	32.0	64.	4.44	0.134E-02	0.141E-02
281	27.92	2.40	25.1	1.37	31.9	64.	2.94	0.299E-02	0.315E-02
282	27.92	1.88	19.7	3.97	31.9	64.	2.27	0.114E-02	0.120E-02
283	27.92	2.40	25.1	5.57	31.9	65.	3.61	0.930E-03	0.968E-03
284	27.92	2.81	29.4	2.57	31.9	65.	4.24	0.128E-02	0.133E-02
285	27.92	1.91	20.0	9.55	31.9	66.	3.10	0.787E-03	0.808E-03
286	27.92	1.89	19.8	14.42	31.9	67.	3.51	0.709E-03	0.718E-03
287	27.92	2.39	25.0	7.12	31.9	67.	4.60	0.934E-03	0.946E-03
288	27.92	2.87	30.0	4.11	31.9	67.	5.35	0.106E-02	0.107E-02
289	27.92	2.90	30.3	5.37	31.9	67.	6.24	0.103E-02	0.104E-02
290	27.92	2.40	25.1	9.15	31.9	68.	5.66	0.939E-03	0.939E-03
291	27.92	1.92	20.1	14.11	31.9	63.	3.77	0.742E-03	0.742E-03
292	27.92	1.85	19.4	13.59	31.9	68.	4.35	0.905E-03	0.905E-03
293	27.92	1.88	19.7	5.79	31.9	58.	2.45	0.704E-03	0.803E-03

RUN NO.	DEPTH (FT)	S.W.VEL (FT/SEC)	QW (GPM)	A/W (V/O)	P.AMB (FTH2O)	TW (F)	DELTA H (FEET)	KL(TW) (FT/SEC)	KL(20 C) (FT/SEC)
295	27.92	1.88	19.7	1.81	32.0	55.	2.09	0.219E-02	0.260E-02
296	27.92	2.33	24.4	0.89	32.0	57.	2.48	0.326E-02	0.377E-02
297	27.92	2.83	29.6	0.67	32.0	57.	3.32	0.460E-02	0.532E-02
298	27.92	2.41	25.2	2.58	32.0	58.	3.01	0.146E-02	0.167E-02
299	27.92	1.94	20.3	4.61	32.0	58.	2.50	0.117E-02	0.133E-02
300	27.92	1.46	15.3	6.02	32.0	59.	1.95	0.904E-03	0.102E-02
301	27.92	1.90	19.9	8.49	32.0	59.	3.10	0.870E-03	0.980E-03
302	27.92	2.80	29.3	2.53	32.0	60.	4.09	0.166E-02	0.184E-02
303	27.92	3.32	34.7	3.79	32.0	60.	3.80	0.134E-03	0.149E-03
304	27.92	2.35	24.6	6.12	32.0	60.	3.56	0.102E-02	0.113E-02
305	27.92	2.32	24.3	7.19	32.0	61.	4.20	0.106E-02	0.116E-02
306	27.92	1.92	20.1	12.44	32.0	62.	3.36	0.857E-03	0.928E-03
307	27.92	2.92	30.5	3.53	31.9	65.	5.01	0.141E-02	0.146E-02
308	27.92	2.84	29.7	4.73	31.9	65.	5.29	0.118E-02	0.122E-02
309	27.92	2.41	25.2	7.82	31.9	65.	4.97	0.103E-02	0.107E-02
310	27.92	1.91	20.0	16.78	31.9	66.	3.95	0.719E-03	0.739E-03
311	27.92	3.41	35.7	1.40	31.9	67.	5.98	0.401E-02	0.407E-02
312	27.92	2.35	24.6	9.40	31.9	67.	5.19	0.983E-03	0.996E-03
313	27.92	1.91	20.0	15.79	31.9	67.	3.71	0.755E-03	0.765E-03
314	27.92	2.88	30.1	5.85	31.9	67.	6.16	0.129E-02	0.130E-02
315	27.92	2.93	30.6	6.51	31.9	68.	6.86	0.107E-02	0.107E-02
316	27.92	2.40	25.1	10.87	31.9	68.	6.01	0.865E-03	0.865E-03
317	27.92	1.94	20.3	17.83	31.9	68.	4.42	0.656E-03	0.656E-03
318	27.92	3.37	35.2	3.67	31.9	68.	7.36	0.144E-02	0.144E-02
320	27.92	1.46	15.3	2.35	31.7	53.	1.63	0.128E-02	0.156E-02
321	27.92	1.43	15.0	3.64	31.7	53.	1.87	0.824E-03	0.100E-02
322	27.92	1.44	15.1	5.68	31.7	54.	1.89	0.633E-03	0.762E-03
323	27.92	1.42	14.9	7.77	31.7	54.	2.00	0.505E-03	0.608E-03
325	27.92	3.40	35.6	4.03	31.7	55.	7.43	0.719E-03	0.853E-03

RUN NO.	DEPTH (FT)	S.W.VEL (FT/SEC)	QW (GPM)	A/W (V/D)	P.AMB (FTH2O)	TW (F)	DELTA H (FEET)	KL(TW) (FT/SEC)	KL(20 C) (FT/SEC)
332	36.50	1.89	19.8	2.71	32.0	66.	2.55	0.324E-02	0.332E-02
333	36.50	1.44	15.1	3.61	32.0	67.	2.15	0.287E-02	0.290E-02
335	36.50	2.80	29.3	0.82	32.0	69.	4.05	0.237E-01	[illegible]
336	36.50	2.41	25.2	2.78	32.0	69.	3.58	0.201E-02	0.198E-02
337	36.50	1.88	19.7	5.78	32.0	70.	2.89	0.226E-02	0.220E-02
338	36.50	1.46	15.3	5.83	32.0	71.	2.32	0.488E-02	0.469E-02
339	36.50	1.87	19.6	9.11	32.0	71.	3.32	0.210E-02	0.202E-02
340	36.50	1.45	15.2	10.39	32.0	72.	2.82	0.127E-02	0.120E-02
341	36.50	2.41	25.2	5.66	32.0	72.	4.16	0.158E-02	0.150E-02
342	36.50	2.87	30.0	3.22	32.0	71.	4.71	0.194E-02	0.186E-02
344	36.50	1.89	19.8	10.77	31.9	74.	4.23	0.103E-02	0.955E-03
345	36.50	2.41	25.2	6.36	31.9	74.	5.44	0.121E-02	0.112E-02
346	36.50	2.83	29.6	3.94	31.9	75.	5.87	0.131E-02	0.120E-02
347	36.50	2.85	29.8	4.51	31.9	75.	6.17	0.112E-02	0.102E-02
348	36.50	2.41	25.2	6.36	31.9	76.	5.79	0.150E-02	0.135E-02
349	36.50	1.91	20.0	14.20	31.9	76.	4.41	0.930E-03	0.837E-03
350	36.50	1.87	19.6	15.79	31.9	76.	4.27	0.893E-03	0.804E-03
356	36.50	1.46	15.3	5.13	31.9	70.	2.84	0.150E-02	0.146E-02
357	36.50	1.41	14.7	7.06	31.9	71.	2.80	0.438E-03	0.421E-03
358	36.50	1.38	14.4	4.98	31.9	71.	2.68	0.277E-02	0.266E-02
359	36.50	1.49	15.6	11.12	31.9	71.	2.72	0.974E-03	0.937E-03
360	36.50	1.45	15.2	11.97	31.9	72.	3.08	0.910E-03	0.863E-03
361	36.50	1.42	14.9	8.40	31.9	72.	3.24	0.110E-02	0.104E-02
362	36.50	1.91	20.0	1.49	31.9	73.	2.88	0.610E-02	0.571E-02
363	36.50	1.92	20.1	2.65	31.9	73.	3.12	0.210E-02	0.197E-02
364	36.50	1.90	19.9	3.86	31.9	73.	3.24	0.154E-02	0.144E-02
365	36.50	1.91	20.0	5.70	31.9	73.	3.47	0.120E-02	0.112E-02

RUN NO.	DEPTH (FT)	S.W.VEL (FT/SEC)	QW (GPM)	A/W (V/O)	P.AMB (FTH2O)	TW (F)	DELTA H (FEET)	KL(TW) (FT/SEC)	KL(20 C) (FT/SEC)
366	36.50	1.90	19.9	7.25	31.9	73.	3.80	0.110E-02	0.103E-02
367	36.50	1.90	19.9	8.53	31.9	73.	3.99	0.111E-02	0.103E-02
368	36.50	1.93	20.2	10.29	31.9	74.	4.18	0.104E-02	0.964E-03
369	36.50	1.88	19.7	12.59	31.9	75.	4.33	0.983E-03	0.896E-03
370	36.50	1.90	19.9	11.73	31.9	75.	3.92	0.941E-03	0.858E-03
371	36.50	1.94	20.3	12.99	31.9	76.	4.21	0.101E-02	0.908E-03
372	36.50	1.86	19.5	11.90	31.9	77.	4.34	0.117E-02	0.104E-02
373	36.50	1.86	19.5	13.12	31.9	77.	3.78	0.971E-03	0.863E-03
374	36.50	1.93	20.2	13.50	31.9	78.	4.32	0.951E-03	0.834E-03
375	36.50	1.43	15.0	7.00	33.0	68.	1.82	0.510E-03	0.510E-03
377	36.50	2.41	25.2	1.96	33.0	70.	3.40	0.522E-02	0.508E-02
378	36.50	2.35	24.6	3.18	33.0	70.	3.48	0.222E-02	0.216E-02
379	36.50	2.39	25.0	5.07	33.0	70.	3.72	0.154E-02	0.150E-02
380	36.50	2.41	25.2	5.94	33.0	70.	4.09	0.145E-02	0.141E-02
381	36.50	2.39	25.0	6.42	33.0	71.	4.44	0.139E-02	0.134E-02
382	36.50	2.39	25.0	6.59	33.0	71.	4.75	0.137E-02	0.132E-02
383	36.50	2.35	24.6	7.55	33.0	71.	4.98	0.134E-02	0.129E-02
384	36.50	2.38	24.9	8.29	33.0	71.	5.28	0.133E-02	0.128E-02
385	36.50	2.38	24.9	9.03	33.0	72.	5.62	0.129E-02	0.122E-02
386	36.50	2.39	25.0	10.02	33.0	72.	6.08	0.119E-02	0.113E-02
388	36.50	2.87	30.0	0.78	31.8	73.	4.17	0.535E-02	0.501E-02
389	36.50	2.81	29.4	1.65	31.8	73.	4.30	0.249E-02	0.234E-02
390	36.50	2.88	30.1	2.37	31.8	74.	4.86	0.172E-02	0.159E-02
391	36.50	2.85	29.8	3.22	31.8	74.	5.18	0.142E-02	0.131E-02
392	36.50	2.83	29.6	3.88	31.8	74.	5.49	0.132E-02	0.122E-02
393	36.50	2.81	29.4	4.25	31.8	75.	5.70	0.129E-02	0.118E-02
394	36.50	2.85	29.8	4.66	31.8	75.	6.06	0.132E-02	0.120E-02
395	36.50	2.88	30.1	5.26	31.8	75.	5.44	0.131E-02	0.120E-02
396	36.50	2.92	30.5	5.65	31.8	75.	5.95	0.127E-02	0.115E-02
397	36.50	3.32	34.7	3.45	31.8	75.	7.50	0.159E-02	0.145E-02
398	36.50	3.23	33.8	2.92	31.8	75.	6.63	0.168E-02	0.153E-02
400	36.50	3.31	34.6	1.70	31.7	54.	5.70	0.149E-02	0.180E-02
401	36.50	3.32	34.7	3.00	31.7	54.	6.51	0.118E-02	0.142E-02
402	36.50	3.37	35.2	3.91	31.7	55.	7.52	0.121E-02	0.144E-02

TABLE B-3. U-TUBE EXPERIMENTAL DATA WITH CALCULATED GAS CONCENTRATIONS AND HEAD LOSSES AT OTHER STATIONS

	D.O. CONCENTRATIONS (MG/L)							D.N. CONC. (MG/L)			HEAD RELATIVE TO INLET (FEET)					
RUN NO.	ENTR	VENTURI EXIT	BEND EXIT	PLATF	EXIT (CALC)	EXIT (EXP)	TRUE EXIT	ENTR	BEND EXIT	TRUE EXIT	VENTURI EXIT	BEND ENTR	BEND EXIT	PLATF	EXIT (EXP)	TRUE EXIT
106	1.65	1.79	3.09	3.69	3.87	3.87	3.80	3.30	7.15	9.27	0.90	2.30	2.37	2.60	2.70	2.61
107	1.63	1.93	3.44	4.20	4.41	4.41	4.31	3.26	8.15	10.59	1.65	3.30	3.41	3.68	3.75	3.67
108	1.63	1.90	3.95	4.90	5.14	5.14	5.04	3.26	9.63	12.52	1.10	3.10	3.17	3.07	3.75	2.96
109	1.55	2.09	4.18	5.22	5.47	5.47	5.35	3.10	10.12	13.13	2.00	4.25	4.37	4.31	5.00	4.19
110	1.63	2.13	5.01	6.29	6.53	6.53	6.42	3.26	12.31	15.31	1.00	4.30	4.37	3.71	4.75	3.41
111	1.52	2.09	5.80	7.24	7.36	7.36	7.30	3.04	12.53	15.49	1.70	4.80	4.87	4.02	5.75	3.67
112	1.43	1.99	3.73	4.61	4.83	4.83	4.69	2.86	8.33	10.98	3.30	5.35	5.53	6.01	6.25	6.02
113	1.36	2.04	4.70	5.94	6.16	6.16	6.04	2.72	10.71	13.78	2.70	5.10	5.22	4.91	6.00	4.73
114	1.28	1.57	3.52	4.21	4.32	4.32	4.25	2.55	5.76	7.57	2.80	4.30	4.48	5.34	5.25	5.46
115	1.43	2.01	4.37	5.43	5.62	5.62	5.50	2.86	8.79	11.58	3.30	5.40	5.57	5.89	5.40	5.87
116	1.49	2.12	6.91	8.36	8.23	8.23	8.27	2.98	12.92	15.76	1.50	5.00	5.07	3.97	5.80	3.54
117	1.60	2.18	4.69	5.86	6.07	6.07	5.95	3.20	10.51	13.47	2.80	5.15	5.27	5.08	5.75	4.94
118	1.50	1.92	3.66	4.48	4.67	4.67	4.56	3.00	7.41	9.77	3.00	4.75	4.93	5.59	5.75	5.65
119	1.41	2.01	4.13	5.12	5.32	5.32	5.19	2.82	8.51	11.21	3.30	5.50	5.68	6.11	6.50	6.11
120	1.61	1.93	3.63	4.45	4.67	4.67	4.57	3.22	8.20	10.82	1.80	3.40	3.52	3.84	4.00	3.85
121	2.32	2.62	5.10	6.19	6.39	6.39	6.30	4.64	11.53	14.39	1.30	3.40	3.47	3.22	4.25	3.06
122	1.94	2.02	2.57	3.28	3.35	3.35	3.32	3.88	5.39	6.38	1.50	2.50	2.62	3.38	3.50	3.54
123	1.90	2.12	3.76	4.48	4.65	4.65	4.55	3.80	7.60	9.77	1.75	3.70	3.82	4.29	4.00	4.34
124	1.79	2.16	3.67	4.42	4.61	4.61	4.49	3.58	7.69	9.97	2.90	4.85	5.03	5.77	5.75	5.85
125	1.69	2.21	3.95	4.44	5.06	5.06	4.92	3.38	8.86	11.56	3.50	5.50	5.68	6.17	6.40	6.19
126	1.67	2.28	5.19	6.47	6.68	6.69	6.57	3.34	11.43	14.53	2.40	5.10	5.21	4.86	5.60	4.67
127	1.92	2.49	6.35	7.84	7.93	7.93	7.88	3.84	13.56	16.43	1.70	4.90	4.97	4.01	5.70	3.62
128	1.74	1.79	4.13	4.13	4.02	4.14	4.00	3.48	6.69	8.43	0.40	1.20	1.23	1.35	2.00	1.35
129	1.46	1.65	2.79	3.28	3.40	3.40	3.33	2.92	5.16	6.55	2.20	3.60	3.77	4.73	4.75	4.89
130	1.54	1.62	2.62	2.93	3.00	3.00	2.97	3.08	4.61	5.50	1.30	2.20	2.31	3.01	3.00	3.16
131	1.44	1.64	2.83	3.33	3.45	3.45	3.38	2.88	5.15	6.56	2.25	3.60	3.78	4.76	4.75	4.92
132	1.92	2.34	4.35	5.32	5.53	5.53	5.43	3.84	9.70	12.45	2.00	3.90	4.02	4.12	4.75	4.06
133	2.20	2.60	5.56	6.78	6.92	6.92	6.85	4.50	11.98	14.74	1.60	4.10	4.17	3.70	4.50	3.47
134	1.72	1.86	3.91	4.59	4.70	4.70	4.66	3.44	7.18	9.28	0.80	2.20	2.27	2.48	2.75	2.49
135	1.41	1.88	3.76	4.65	4.86	4.86	4.73	2.82	7.86	10.43	4.20	5.10	5.27	5.77	6.00	5.80
136	1.74	2.34	5.11	6.32	6.49	6.49	6.39	3.48	10.84	13.74	2.80	5.40	5.52	5.26	6.00	5.11
137	1.66	2.29	5.92	7.34	7.44	7.44	7.39	3.32	12.53	15.37	2.20	5.30	5.38	4.49	5.80	4.15
138	1.88	2.39	4.30	5.22	5.41	5.41	5.29	3.76	9.06	11.60	3.40	5.50	5.67	6.07	6.25	6.07

RUN NO.	D.O. CONCENTRATIONS (MG/L) ENTR	VENTURI EXIT	BEND EXIT	PLATF	EXIT (CALC)	EXIT (EXP)	TRUE EXIT	D.N. CONC.(MG/L) ENTR	BEND EXIT	TRUE EXIT	HEAD RELATIVE TO INLET (FEET) VENTURI EXIT	BEND ENTR	BEND EXIT	PLATF	EXIT (EXP)	TRUE EXIT
139	1.51	1.60	2.71	3.04	3.10	3.10	3.07	3.02	4.62	5.66	1.40	2.40	2.52	3.23	3.30	3.38
140	1.53	1.80	3.47	4.23	4.42	4.42	4.33	3.06	7.22	9.53	1.50	3.10	3.22	3.63	4.00	3.67
141	1.45	1.96	4.17	5.22	5.46	5.46	5.34	2.90	9.59	12.57	2.10	4.20	4.32	4.32	5.00	4.23
142	1.59	2.18	4.73	5.91	6.12	6.12	6.01	3.18	10.63	13.61	2.50	4.90	5.02	4.77	5.70	4.62
143	1.53	2.17	5.04	6.30	6.50	6.50	6.39	3.06	11.03	14.06	2.80	5.30	5.42	5.05	5.75	4.87
144	1.45	1.95	3.55	4.37	4.58	4.58	4.45	2.90	7.87	10.39	3.50	5.35	5.54	6.14	6.25	6.18
145	1.37	2.01	4.19	5.24	5.46	5.46	5.32	2.74	9.06	11.93	3.40	5.70	5.87	6.13	6.30	6.10
147	1.66	1.99	3.52	4.22	4.38	4.38	4.29	3.32	6.85	8.84	2.35	3.90	4.07	4.81	5.00	4.90
148	1.75	2.18	3.83	4.62	4.80	4.80	4.69	3.50	7.79	10.04	2.90	4.70	4.88	5.52	5.80	5.58
149	2.16	2.73	6.30	7.66	7.70	7.70	7.68	4.32	13.16	15.65	2.00	5.10	5.17	4.15	5.50	3.74
150	2.16	2.58	5.84	7.08	7.16	7.16	7.12	4.32	11.98	14.70	1.70	4.30	4.37	3.85	4.70	3.60
151	1.95	2.18	4.96	5.55	6.07	6.07	6.02	3.90	9.67	12.38	1.30	3.10	3.16	3.08	4.00	2.98
152	2.06	2.17	5.14	5.07	4.83	5.08	4.84	4.12	7.24	9.10	1.00	2.35	2.42	2.71	2.80	2.74
153	2.57	2.66	4.40	4.88	4.95	4.95	4.92	5.14	8.04	9.79	0.80	2.00	2.07	2.41	2.25	2.46
154	2.64	2.76	5.17	5.85	5.93	5.93	5.90	5.28	9.45	11.78	0.90	2.20	2.26	2.45	2.80	2.45
155	2.70	2.91	5.62	6.64	6.80	6.80	6.73	5.40	11.33	14.22	1.30	3.00	3.07	3.05	3.60	2.97
156	2.79	3.19	6.78	8.23	8.38	8.38	8.31	5.58	14.81	17.83	1.50	4.25	4.32	3.63	4.75	3.33
157	2.58	3.08	7.00	8.54	8.65	8.65	8.60	5.16	15.01	17.96	1.75	4.85	4.92	4.02	5.10	3.65
158	2.37	2.87	5.63	6.89	7.10	7.10	6.99	4.74	12.33	15.46	2.35	4.70	4.81	4.60	5.20	4.46
159	2.28	2.63	4.89	5.90	6.10	6.10	6.00	4.56	10.13	12.95	2.00	3.80	3.92	4.15	4.40	4.13
160	2.25	2.49	4.56	5.41	5.58	5.58	5.50	4.50	8.96	11.44	1.70	3.15	3.26	3.61	3.70	3.63
161	2.25	2.37	4.02	4.45	4.50	4.50	4.48	4.50	6.84	8.33	1.40	2.50	2.61	3.23	3.00	3.35
162	2.34	2.91	5.97	7.12	7.33	7.33	7.28	4.68	12.64	15.72	2.50	5.20	5.32	5.00	5.80	4.83
163	2.14	2.57	4.41	5.31	5.52	5.52	5.39	4.28	9.31	11.92	3.40	5.30	5.49	6.03	6.25	6.07
164	2.14	2.59	4.56	5.53	5.70	5.70	5.57	4.28	9.32	11.94	3.50	5.30	5.48	6.05	6.30	6.09
165	2.05	2.34	4.90	4.74	4.90	4.90	4.80	4.10	7.68	9.78	2.80	4.40	4.58	5.39	5.60	5.49

RUN NO.	-------- D.O. CONCENTRATIONS (MG/L) ENTR	VENTURI EXIT	BEND EXIT	PLATE	EXIT (CALC)	EXIT (EXP)	TRUE EXIT --------	D.N. CONC.(MG/L) ENTR	BEND EXIT	TRUE EXIT	---- HEAD RELATIVE TO INLET (FEET) VENTURI EXIT	BEND ENTR	BEND EXIT	PLATE	EXIT (EXP)	TRUE EXIT ----
180	1.94	2.09	2.87	3.12	3.50	3.50	3.37	3.88	6.29	8.01	1.40	2.00	2.11	2.22	2.50	2.32
181	1.89	2.12	3.53	4.03	4.63	4.63	4.49	3.78	8.92	11.76	1.15	1.95	2.02	1.98	2.50	1.88
182	2.14	2.47	3.82	4.25	4.91	4.91	4.69	4.29	10.41	13.30	1.35	2.35	2.42	2.33	2.70	2.15
183	2.33	2.59	3.40	3.73	4.23	4.23	4.06	4.76	7.93	10.01	1.80	2.40	2.51	2.57	3.00	2.61
185	2.27	2.47	3.29	3.54	3.92	3.92	3.77	4.54	6.53	8.36	2.20	2.80	2.97	3.15	3.50	3.32
186	2.41	2.79	3.45	4.34	4.91	4.91	4.69	4.82	9.27	11.78	1.80	2.80	2.93	2.93	3.30	2.88
187	2.41	2.79	4.70	5.27	6.03	6.03	5.79	4.82	11.65	14.31	1.60	2.80	2.87	2.70	3.20	2.42
188	2.30	2.76	4.01	4.42	5.03	5.03	4.79	4.60	9.54	12.12	1.15	3.20	3.33	3.30	3.60	3.22
189	2.30	2.82	4.80	5.51	6.31	6.31	6.03	4.60	12.38	14.83	1.80	3.30	3.38	3.12	4.00	2.73
190	2.13	2.37	3.24	3.51	3.92	3.92	3.73	4.26	6.52	8.11	2.65	3.50	3.68	3.86	3.80	4.01
191	2.22	2.61	3.60	3.93	4.44	4.44	4.20	4.44	7.94	10.12	2.80	3.65	3.93	3.93	4.20	3.99
192	2.28	2.86	4.51	5.03	5.74	5.74	5.45	4.56	10.62	13.30	2.50	3.65	3.78	3.65	4.50	3.45
193	2.36	2.86	4.33	5.55	6.33	6.33	6.06	4.72	12.31	14.72	1.60	3.20	3.27	3.02	3.65	2.64
194	2.25	2.33	4.52	5.05	5.76	5.76	5.44	4.50	10.59	13.22	2.85	4.15	4.27	4.13	4.80	3.93
195	2.11	2.59	3.71	4.03	4.64	4.64	4.35	4.22	9.17	10.51	3.10	4.20	4.39	4.46	5.00	4.50
196	2.11	2.65	3.83	4.22	4.81	4.81	4.50	4.22	8.61	11.36	3.60	4.60	4.79	4.93	5.25	4.83
197	2.19	2.79	4.60	5.15	5.91	5.91	5.58	4.38	10.00	13.57	2.90	4.20	4.32	4.15	5.25	3.91
198	1.81	2.50	4.24	4.84	5.60	5.60	5.25	3.62	10.54	13.26	3.00	4.50	4.67	4.43	5.50	4.19
199	1.67	2.34	3.34	3.69	4.25	4.25	3.93	3.34	9.43	11.98	4.25	5.35	5.54	5.55	6.20	5.52
200	2.08	2.72	4.22	4.71	5.41	5.41	5.07	4.16	10.41	13.17	3.35	4.70	4.83	4.68	5.80	4.49
201	2.06	2.69	3.81	4.21	4.78	4.78	4.46	4.17	9.18	11.72	4.00	5.15	5.33	5.30	6.20	5.23
203	2.17	2.27	3.24	3.67	3.75	3.75	3.67	4.34	5.73	6.90	1.40	2.00	2.11	2.25	2.50	2.40
204	1.92	2.09	3.35	3.72	4.29	4.29	4.11	3.94	7.94	10.44	1.20	1.95	2.02	2.02	2.25	1.99
205	1.99	2.33	3.68	4.11	4.79	4.79	4.56	5.98	10.55	13.55	1.40	2.35	2.42	2.31	2.75	2.11
206	1.83	2.27	3.92	4.44	5.21	5.21	4.94	3.66	11.08	14.07	1.70	2.75	2.83	2.66	3.25	2.39
207	1.83	2.38	4.24	4.92	5.65	5.65	5.35	3.66	12.13	14.90	1.90	3.30	3.38	3.13	3.80	2.75
208	1.74	2.35	4.30	4.90	5.76	5.76	5.43	3.48	12.44	15.03	2.30	3.75	3.83	3.52	3.90	3.10
209	1.81	2.39	3.64	4.03	4.75	4.75	4.46	3.62	10.07	12.98	2.60	3.75	3.87	3.75	4.50	3.57
210	1.93	2.44	3.92	4.28	4.93	4.93	4.66	3.66	10.11	13.04	3.00	4.15	4.28	4.16	5.00	3.99
211	1.64	2.40	4.04	4.57	5.35	5.35	4.98	3.28	10.74	13.65	3.20	4.65	4.78	4.58	5.50	4.33
212	1.73	2.11	3.21	3.57	4.14	4.14	3.92	3.46	8.19	10.80	1.75	2.70	2.82	2.82	3.50	2.78
213	1.55	1.65	2.66	2.89	3.19	3.19	3.11	3.10	4.67	5.97	1.50	2.00	2.11	2.25	2.50	2.40
215	1.47	1.66	2.43	2.65	3.02	3.02	2.87	2.94	4.79	6.13	2.20	2.85	3.03	3.23	3.50	3.44
216	1.45	1.79	2.67	2.96	3.42	3.42	3.20	2.90	6.02	8.08	2.85	3.65	3.83	3.97	4.25	4.08
217	1.55	2.07	3.02	3.35	3.88	3.88	3.61	3.10	7.47	10.33	3.40	4.35	4.54	4.61	5.25	4.65
218	1.45	2.09	3.09	3.44	4.01	4.01	3.70	2.90	7.99	10.75	4.00	5.00	5.19	5.21	5.80	5.20
219	1.45	2.11	3.16	3.52	4.10	4.10	3.77	2.90	8.10	10.86	4.35	5.25	5.44	5.46	6.10	5.44

RUN NO.	-------- D.O. ENTR	CONCENTRATIONS VENTURI EXIT	(MG/L) BEND EXIT	PLATE	EXIT (CALC)	EXIT (EXP)	-------- TRUE EXIT	D.N. ENTR	CONC.(MG/L) BEND EXIT	TRUE EXIT	---- HEAD VENTURI EXIT	RELATIVE BEND ENTR	TO INLET BEND EXIT	(FEET) PLATE	EXIT (EXP)	---- TRUE EXIT
225	1.62	1.93	2.31	2.31	2.99	2.99	2.66	3.24	4.96	6.82	1.70	1.90	2.01	4.34	2.50	4.40
226	1.94	2.13	2.95	2.95	3.36	3.96	3.55	3.98	6.37	8.90	1.10	1.45	1.52	3.85	2.50	3.79
227	1.68	1.92	2.88	2.88	4.04	4.04	3.57	3.36	6.37	9.20	1.20	1.55	1.62	3.95	3.00	3.86
228	1.62	1.87	2.53	2.53	3.40	3.40	2.98	3.24	5.16	7.19	1.60	2.25	2.37	4.70	3.00	4.75
229	1.70	2.21	2.39	2.39	4.08	4.08	3.48	3.40	6.36	9.94	2.70	3.15	3.28	5.61	4.00	5.52
230	1.70	2.12	3.31	3.31	4.77	4.77	4.13	3.40	7.73	11.41	1.65	2.15	2.23	4.56	4.00	4.35
231	1.77	2.36	3.46	3.46	4.83	4.83	4.19	3.54	8.75	12.41	1.90	2.65	2.73	5.06	5.00	4.74
232	1.60	2.29	3.20	3.20	4.46	4.46	3.76	3.20	7.73	11.24	2.80	3.40	3.52	5.85	5.00	5.65
233	1.53	2.45	3.34	3.34	4.60	4.60	3.78	3.06	8.31	11.95	3.80	4.60	4.74	7.07	6.00	6.83
234	1.70	2.84	4.23	4.23	6.04	6.04	5.18	3.40	10.63	13.37	2.20	3.50	3.59	5.92	6.00	5.22
235	1.67	1.75	1.94	1.94	2.20	2.20	2.97	3.34	3.85	4.42	1.90	2.15	2.32	4.65	3.00	4.85
236	1.57	1.91	2.45	2.45	3.22	3.22	2.80	3.14	5.10	7.07	2.50	2.80	2.98	5.31	3.75	5.39
237	1.55	2.09	2.67	2.67	3.53	3.53	3.01	3.10	5.95	8.56	3.10	3.50	3.68	6.01	4.50	6.02
238	1.53	2.13	2.52	2.52	3.15	3.15	2.73	3.06	6.02	9.66	3.75	4.20	4.40	6.73	5.00	6.73
239	1.45	2.16	2.63	2.63	3.49	3.49	2.94	2.90	6.43	9.40	4.20	4.65	4.84	7.17	5.75	7.13
240	1.43	2.20	2.72	2.72	3.54	3.54	2.94	2.86	6.55	9.58	4.75	5.25	5.45	7.78	6.50	7.73
241	1.35	2.22	2.80	2.80	3.70	3.70	3.01	2.70	6.63	9.93	5.15	5.75	5.96	8.29	7.25	8.23
242	1.63	1.87	2.36	2.36	3.03	3.03	2.72	3.36	4.87	6.53	1.65	1.90	2.02	4.35	2.50	4.41
243	1.66	1.88	2.71	2.71	3.74	3.74	3.30	3.32	6.05	8.77	1.25	1.60	1.67	4.00	2.50	3.93
244	1.41	1.59	1.93	1.93	2.41	2.41	2.16	2.82	3.30	4.34	2.20	2.50	2.68	5.01	3.30	5.18
245	1.40	1.81	2.72	2.72	3.93	3.93	3.34	2.80	5.76	8.56	1.80	2.20	2.32	4.65	3.50	4.61
246	1.40	1.79	2.90	2.90	4.28	4.28	3.70	2.90	6.94	10.47	1.35	1.85	1.92	4.25	3.50	4.07
247	1.39	1.75	2.16	2.16	2.77	2.77	2.41	2.78	4.63	6.43	3.00	3.30	3.49	5.82	4.25	5.91
248	1.39	2.00	2.76	2.76	3.83	3.83	3.22	2.78	6.82	10.14	2.90	3.40	3.53	5.86	4.50	5.71
249	1.39	1.93	3.28	3.28	4.89	4.89	4.18	2.78	8.01	11.30	1.70	2.35	2.42	4.75	4.50	4.45
250	1.37	1.99	2.59	2.59	3.47	3.47	2.90	2.74	[illegible]	8.53	3.70	4.10	4.29	6.62	5.25	6.60
251	1.37	2.16	3.04	3.04	4.27	4.27	3.50	2.74	7.37	10.23	3.65	4.25	4.39	6.72	5.50	6.53
252	1.37	2.26	3.69	3.69	5.40	5.40	4.61	2.74	9.06	12.75	2.20	2.90	2.99	5.32	5.50	4.84
253	1.45	1.66	2.10	2.10	2.73	2.73	2.43	2.90	4.65	6.53	1.55	1.90	2.01	4.34	2.50	4.39
254	1.45	1.66	2.44	2.44	3.42	3.42	3.00	2.90	5.48	8.17	1.20	1.60	1.67	4.00	2.50	3.96
255	1.56	2.09	2.68	2.68	3.55	3.55	3.05	3.12	6.63	9.72	2.70	3.15	3.28	5.61	4.00	5.52
256	1.42	1.72	2.14	2.14	2.76	2.76	2.41	2.84	4.52	6.22	2.75	3.00	3.18	5.51	3.75	5.60
257	1.59	2.02	3.12	3.12	4.51	4.51	3.90	3.18	7.77	11.42	1.50	2.00	2.07	4.40	4.00	4.16
258	1.42	2.21	3.02	3.02	4.13	4.13	3.45	2.84	7.49	11.03	3.65	4.25	4.39	6.72	5.50	6.54
259	1.34	1.35	2.58	2.58	3.51	3.51	2.91	2.68	5.80	9.55	3.75	4.25	4.43	6.76	5.00	6.75
260	1.41	2.13	3.53	3.53	5.21	5.21	4.41	2.82	8.71	12.55	2.20	2.90	2.99	5.32	5.50	4.94
261	1.41	2.28	3.36	3.36	4.80	4.80	3.88	2.82	7.94	11.56	3.80	4.60	4.73	7.06	7.00	6.84
262	1.24	1.99	2.62	2.62	3.56	3.56	2.87	2.43	6.08	9.07	4.90	5.40	5.60	7.93	6.75	7.89
263	1.50	2.31	3.63	3.63	5.27	5.27	4.52	3.00	9.45	13.21	1.75	2.65	2.73	5.06	7.00	4.58

	-------- D.O. CONCENTRATIONS (MG/L) -------							D.N. CONC.(MG/L)			---- HEAD RELATIVE TO INLET (FEET) ----					
RUN NO.	ENTR	VENTURI EXIT	BEND EXIT	PLATE	EXIT (CALC)	EXIT (EXP)	TRUE EXIT	ENTR	BEND EXIT	TRUE EXIT	VENTURI EXIT	BEND ENTR	BEND EXIT	PLATE	EXIT (EXP)	TRUE EXIT
273	1.88	2.14	4.05	4.81	5.27	5.27	5.11	3.76	10.46	13.41	1.15	2.45	2.52	2.42	3.00	2.30
274	1.88	2.08	3.10	3.54	3.84	3.84	3.72	3.76	7.32	9.45	1.50	2.35	2.46	2.67	3.00	2.74
275	1.81	2.03	2.76	3.10	3.34	3.34	3.21	3.62	6.30	8.02	2.20	3.00	3.17	3.58	4.00	3.74
276	1.81	2.07	4.10	4.79	5.15	5.15	5.00	3.62	8.09	10.65	1.65	3.25	3.36	3.51	4.00	3.54
277	1.96	2.41	4.55	5.46	5.58	5.58	5.73	3.92	12.90	15.72	1.65	3.35	3.42	3.08	4.00	2.80
278	1.96	2.59	5.26	6.34	6.88	6.88	6.66	3.92	14.67	16.74	1.80	4.20	4.28	3.66	5.00	3.22
279	1.88	2.43	4.72	5.14	5.63	5.63	5.40	3.76	11.40	14.35	2.40	4.15	4.27	4.10	5.00	3.95
280	1.79	2.19	3.32	3.95	4.20	4.20	4.02	3.58	8.00	10.47	2.85	3.90	4.08	4.36	5.00	4.44
281	2.40	2.52	3.66	4.06	4.27	4.27	4.19	4.80	7.05	8.55	1.35	2.40	2.57	2.91	3.00	2.94
282	2.49	2.72	4.48	5.15	5.61	5.61	5.46	4.98	11.10	13.80	1.25	2.40	2.47	2.38	3.00	2.27
283	2.38	2.85	4.35	5.04	5.46	5.46	5.27	4.76	11.36	14.09	2.15	3.70	3.82	3.73	4.50	3.61
284	2.29	2.58	3.45	3.36	4.14	4.14	4.00	4.56	8.06	10.12	2.50	3.65	3.82	4.14	4.50	4.24
285	2.44	2.92	5.19	6.13	6.61	6.61	6.42	4.88	14.08	16.21	1.70	3.85	3.92	3.45	4.50	3.10
286	2.49	3.26	6.13	7.24	7.65	7.65	7.47	4.98	15.71	16.75	1.65	5.00	5.08	4.13	6.00	3.51
287	2.24	2.82	4.60	5.40	5.85	5.85	5.62	4.48	11.99	14.57	3.15	4.90	5.02	4.78	6.00	4.60
288	1.98	2.45	3.53	4.04	4.39	4.39	4.19	3.96	8.96	11.49	3.65	4.95	5.13	5.32	6.00	5.35
289	1.98	2.63	3.91	4.51	4.90	4.90	4.66	3.96	9.98	12.59	2.50	6.00	6.19	6.26	7.50	6.24
290	2.18	2.91	5.06	5.90	6.35	6.35	6.09	4.36	12.70	14.98	3.50	6.20	6.33	5.90	7.50	5.66
291	2.44	3.21	6.07	7.17	7.57	7.57	7.39	4.88	15.41	16.51	2.00	5.20	5.28	4.35	7.50	3.77
292	2.52	3.44	7.21	8.50	8.61	8.61	8.55	5.04	15.93	16.52	2.20	6.30	6.38	5.08	8.25	4.35
293	2.85	3.17	4.88	5.62	6.08	6.08	5.91	5.70	13.67	16.34	1.30	2.85	2.92	2.67	3.50	2.45
295	2.39	2.50	4.14	4.67	4.96	4.96	4.87	4.78	8.55	10.75	0.95	1.90	1.96	2.07	2.50	2.09
296	2.13	2.21	3.13	3.42	3.58	3.58	3.53	4.26	5.99	7.17	1.20	1.90	2.01	2.32	2.50	2.49
297	2.22	2.30	3.05	3.27	3.38	3.39	3.34	4.44	5.60	6.44	1.70	2.40	2.57	3.08	3.50	3.32
298	2.39	2.62	3.98	4.42	4.77	4.77	4.63	4.78	8.88	11.26	1.65	2.65	2.77	2.95	3.50	3.01
299	2.58	2.86	4.98	5.83	6.30	6.30	6.11	5.16	12.22	15.17	1.30	2.70	2.77	2.64	3.50	2.50
300	2.64	2.86	5.66	6.67	7.17	7.17	7.01	5.28	14.96	17.39	0.75	2.55	2.58	2.24	3.50	1.95
301	2.64	3.11	5.78	6.84	7.36	7.36	7.15	5.28	15.04	17.37	1.80	3.85	3.92	3.45	4.50	3.10
302	2.43	2.71	3.88	4.35	4.67	4.67	4.52	4.86	8.45	10.61	2.40	3.50	3.67	3.99	4.50	4.09
303	2.05	2.63	2.76	2.94	2.90	2.90	2.87	4.10	8.91	11.41	2.25	3.00	3.25	3.67	4.50	3.80
304	2.43	2.93	4.84	5.68	6.16	6.16	5.95	4.86	12.32	15.22	2.00	3.75	3.87	3.71	4.50	3.56
305	2.49	3.35	5.24	6.16	6.65	6.65	6.42	4.98	12.98	15.70	2.65	4.55	4.67	4.40	5.50	4.20

RUN NO.	D.O. CONCENTRATIONS (MG/L) ENTR	VENTURI EXIT	BEND EXIT	PLATE	EXIT (CALC)	EXIT (EXP)	TRUE EXIT	D.N. CONC.(MG/L) ENTR	BEND EXIT	TRUE EXIT	HEAD RELATIVE TO INLET (FEET) VENTURI EXIT	BEND ENTR	BEND EXIT	PLATE	EXIT (EXP)	TRUE EXIT
306	2.61	3.30	6.50	7.69	6.12	6.12	7.95	5.22	16.02	17.51	1.75	4.60	4.68	3.89	5.50	3.36
307	2.02	2.44	3.56	4.22	4.58	4.58	4.34	4.04	8.56	11.22	3.25	4.50	4.69	4.95	5.50	5.01
308	2.11	2.64	3.99	4.62	5.02	5.02	4.73	4.22	9.79	12.45	3.50	5.00	5.18	5.30	6.50	5.29
309	2.20	2.45	4.57	5.77	6.34	6.34	6.09	4.41	12.45	15.03	3.25	5.35	5.48	5.17	6.50	4.97
310	2.35	3.27	6.45	7.63	6.00	6.00	7.83	4.70	15.92	16.80	3.00	5.70	5.78	4.64	6.50	3.95
311	2.24	2.45	3.44	3.83	4.04	4.04	3.92	4.48	6.33	7.57	3.75	4.65	5.11	5.78	6.25	5.98
312	2.15	2.89	5.20	6.16	6.62	6.62	6.37	4.31	13.02	15.31	3.35	5.80	5.92	5.46	7.50	5.19
313	2.32	3.19	6.36	7.54	7.91	7.91	7.75	4.64	15.73	16.70	1.85	5.35	5.43	4.37	7.50	3.71
314	1.89	2.55	4.24	4.98	5.42	5.42	5.15	3.78	10.15	12.88	4.10	6.00	6.19	6.21	7.25	6.14
315	1.96	2.69	4.17	4.36	5.28	5.28	5.00	3.92	10.47	13.09	4.80	6.75	6.95	6.92	9.25	6.86
316	1.96	2.84	5.07	6.02	5.43	6.49	6.20	3.92	13.11	15.20	3.95	6.75	6.88	6.29	8.50	6.01
317	2.22	3.22	6.16	7.26	7.67	7.67	7.48	4.44	15.52	16.35	2.25	6.25	6.34	5.11	8.50	4.42
318	1.96	2.44	3.52	4.02	4.35	4.35	4.12	3.42	8.12	10.36	5.00	6.60	6.86	7.29	7.70	7.36
320	2.03	3.02	4.79	5.40	5.76	5.76	5.66	5.86	11.27	13.80	0.65	1.70	1.73	1.69	2.50	1.63
321	2.33	2.38	4.67	5.50	6.06	6.06	5.91	5.66	13.25	16.02	0.70	2.15	2.18	2.02	3.00	1.97
322	3.09	3.28	5.41	6.27	6.78	6.78	6.62	6.18	15.70	18.33	0.70	2.45	2.48	2.16	3.50	1.99
323	2.89	3.15	5.48	6.43	6.58	5.98	6.80	5.78	17.18	18.88	0.50	2.85	2.88	2.39	4.00	2.09
325	2.95	3.45	4.11	4.47	4.72	4.72	4.54	5.90	12.37	12.70	5.15	6.70	6.96	7.36	7.90	7.43

RUN NO.	ENTR	VENTURI EXIT	BEND EXIT	PLATE	EXIT (CALC)	EXIT (EXP)	TRUE EXIT	ENTR	BEND EXIT	TRUE EXIT	VENTURI EXIT	BEND ENTR	BEND EXIT	PLATE	EXIT (EXP)	TRUE EXIT
	-------- D.O. CONCENTRATIONS (MG/L) - -----							D.O. CONC.(MG/L)			---- HEAD RELATIVE TO INLET (FEET) ----					
332	1.66	1.84	5.12	5.81	5.15	5.85	5.82	3.32	8.68	11.49	1.10	2.45	2.52	2.58	3.00	2.55
333	1.73	1.88	6.41	7.07	6.92	7.17	6.93	3.46	11.36	14.54	0.70	2.45	2.48	2.29	3.00	2.15
334	1.54	1.58	2.17	2.30	2.93	3.33	2.32	3.08	3.89	4.44	1.35	2.25	2.36	2.90	3.00	3.08
335	1.44	1.55	3.16	3.13	3.06	3.13	3.05	2.88	4.30	5.40	1.55	2.95	3.11	3.85	4.00	4.06
336	1.44	1.72	3.78	4.57	4.82	4.82	4.71	2.48	7.53	10.08	1.75	3.15	3.27	3.54	4.00	3.58
337	1.42	1.40	6.58	7.68	7.61	7.61	7.52	2.84	11.72	14.97	1.35	3.35	3.42	3.10	4.00	2.99
338	1.65	1.89	8.82	8.74	7.75	8.35	7.76	3.30	13.59	16.55	0.60	3.00	3.03	2.59	4.00	2.37
339	1.90	2.44	8.25	9.28	8.77	8.77	8.92	3.80	14.21	16.68	1.75	4.35	4.42	3.70	5.00	3.32
340	1.80	2.21	7.57	9.19	8.65	8.95	8.94	3.60	15.93	17.43	0.90	4.25	4.29	3.32	5.00	2.97
341	1.80	2.32	8.20	6.71	6.55	6.55	6.53	3.60	10.79	13.70	2.20	4.25	4.37	4.28	5.00	4.16
342	1.65	2.06	3.91	4.70	4.96	4.96	4.82	3.30	7.89	10.35	2.50	4.00	4.18	4.63	5.00	4.71
344	1.68	2.34	6.43	7.77	7.95	7.65	7.81	3.36	14.13	16.12	1.70	5.50	5.57	4.64	6.00	4.23
345	1.60	2.19	4.13	5.80	6.09	6.09	5.92	3.20	10.84	13.63	2.80	5.65	5.77	5.57	6.00	5.44
346	1.27	1.78	3.38	4.15	4.44	4.44	4.26	2.54	7.92	10.54	3.00	5.35	5.52	5.85	5.75	5.87
347	1.27	1.85	3.44	4.22	4.52	4.52	4.33	2.54	8.50	11.22	3.75	5.75	5.93	6.17	5.75	6.17
348	1.34	1.95	4.92	6.05	6.29	6.29	6.15	2.68	10.41	14.26	3.35	6.00	6.12	5.91	7.00	5.79
349	1.57	2.44	6.76	8.13	8.10	8.10	8.10	3.14	14.44	16.04	2.30	6.20	6.28	4.96	7.00	4.41
350	1.57	2.51	7.04	8.45	8.34	9.04	8.38	3.14	14.71	16.21	2.00	6.30	6.38	4.89	8.00	4.27
351	1.56	2.49	5.59	6.22	7.00	7.00	6.89	3.12	12.34	14.68	3.60	6.65	6.77	6.11	8.00	5.85
355	1.59	1.74	5.51	6.36	6.43	6.43	6.39	3.18	10.69	13.59	0.70	3.00	3.03	2.84	3.00	2.71
356	1.59	1.80	5.46	7.07	7.18	7.14	7.13	3.18	12.59	15.50	0.75	3.40	3.43	3.06	3.50	2.84
357	1.57	1.85	4.07	5.07	5.45	5.45	5.30	3.14	14.16	16.25	0.60	3.70	3.73	3.12	4.00	2.80
358	1.57	1.76	7.32	7.55	7.57	7.60	7.64	3.14	12.81	15.74	0.65	3.25	3.28	2.90	4.50	2.58
359	1.57	2.04	7.24	8.66	8.59	8.59	8.60	3.14	15.03	17.43	1.00	4.25	4.29	3.25	5.00	2.72
360	1.55	2.03	7.28	8.69	8.59	8.59	8.61	3.10	16.09	17.30	1.00	4.75	4.79	3.64	5.50	3.08
361	1.47	1.81	6.69	8.00	8.02	8.02	8.01	2.94	14.90	16.87	0.85	4.35	4.38	3.62	6.00	3.24
362	1.22	1.33	3.79	4.03	3.58	4.05	3.98	2.44	5.66	7.56	0.95	2.55	2.62	2.84	2.50	2.99
363	1.38	1.57	3.56	4.73	4.94	4.94	4.86	2.76	7.75	10.33	1.05	3.00	3.07	3.14	3.00	3.12
364	1.30	1.57	4.27	5.24	5.51	5.51	5.40	2.60	9.26	13.23	1.20	3.35	3.42	3.33	3.50	3.24

RUN NO.	D.O. CONCENTRATIONS (MG/L) ENTR	VENTURI EXIT	BEND EXIT	PLATE	EXIT (CALC)	EXIT (EXP)	TRUE EXIT	D.N. CONC.(MG/L) ENTR	BEND EXIT	TRUE EXIT	HEAD RELATIVE TO INLET (FEET) VENTURI EXIT	BEND ENTR	BEND EXIT	PLATE	EXIT (EXP)	TRUE EXIT
365	1.38	1.77	4.80	5.94	6.24	6.24	6.11	2.76	11.19	14.18	1.35	3.90	3.97	3.66	4.00	3.47
366	1.38	1.86	5.28	6.54	6.90	6.80	6.64	2.76	12.35	15.13	1.60	4.50	4.57	4.07	4.50	3.80
367	1.38	1.94	5.76	7.09	7.29	7.29	7.20	2.76	13.07	15.64	1.75	4.90	4.97	4.31	5.00	3.99
368	1.44	2.12	6.12	7.49	7.62	7.62	7.55	2.88	13.69	15.91	1.65	5.35	5.43	4.57	5.50	4.19
369	1.67	2.44	6.74	8.10	8.05	8.09	8.09	3.34	14.51	16.18	1.75	5.90	5.97	4.82	6.00	4.33
370	1.50	2.24	6.26	7.64	7.75	7.75	7.70	3.00	14.13	16.06	1.95	5.35	5.42	4.39	6.00	3.92
371	1.58	2.41	6.70	8.06	8.04	8.06	8.04	3.16	14.25	16.00	2.05	5.80	5.88	4.71	6.50	4.21
372	1.47	2.20	6.17	8.18	8.07	8.07	8.11	2.96	14.05	15.85	1.95	5.80	5.87	4.80	7.00	4.34
373	1.40	2.21	6.62	8.00	7.99	7.99	7.98	2.80	14.28	16.01	1.75	5.45	5.52	4.32	7.50	3.79
374	1.38	1.82	6.42	5.99	5.96	5.96	5.83	3.06	14.53	17.06	0.68	2.70	2.73	2.16	2.80	1.82
375	1.53	1.91	4.40	5.54	5.96	5.96	5.83	3.06	15.79	17.81	0.68	2.70	2.73	1.95	2.80	1.49
376	1.31	1.40	2.66	2.54	3.00	3.86	2.98	2.62	4.37	5.51	1.40	2.25	2.36	2.88	3.00	3.06
377	1.38	1.59	4.24	4.73	4.75	4.75	4.73	2.76	6.31	8.46	1.60	2.80	2.92	3.31	3.50	3.40
378	1.38	1.70	4.22	5.11	5.35	5.35	5.24	2.76	8.04	10.83	1.75	3.15	3.26	3.47	4.00	3.49
379	1.55	2.08	4.81	5.91	6.21	6.21	6.07	3.10	10.24	13.38	1.95	3.70	3.82	3.80	4.50	3.72
380	1.73	2.11	5.21	6.36	6.65	6.65	6.51	3.46	11.15	14.24	2.10	4.20	4.32	4.21	5.00	4.09
381	1.71	2.32	5.30	6.47	6.75	6.75	6.61	3.42	11.41	14.44	2.50	4.65	4.77	4.58	5.50	4.44
382	1.71	2.36	5.37	6.66	6.83	6.83	6.69	3.42	11.57	14.58	2.80	5.00	5.12	4.89	6.00	4.75
383	1.71	2.39	5.68	6.93	7.17	7.17	7.04	3.42	12.16	15.08	2.90	5.40	5.52	5.16	6.50	4.98
384	1.79	2.54	5.95	7.23	7.43	7.43	7.31	3.58	12.57	15.38	3.15	5.80	5.92	5.49	7.00	5.28
385	1.78	2.58	6.07	7.35	7.53	7.53	7.42	3.56	12.80	15.46	3.35	6.25	6.37	5.84	7.50	5.62
386	1.78	2.66	6.14	7.44	7.61	7.61	7.50	3.56	13.13	15.63	3.75	6.85	6.98	6.32	8.00	6.08
387	1.45	1.49	1.85	1.56	2.00	2.50	1.98	2.90	3.42	3.77	1.60	2.55	2.73	3.60	3.50	3.85
388	1.45	1.56	2.57	2.84	2.90	2.90	2.87	2.90	4.24	5.15	1.95	3.00	3.17	3.96	4.00	4.17
389	1.45	1.66	2.93	3.44	3.62	3.62	3.53	2.90	5.57	7.22	2.15	3.35	3.52	4.15	4.50	4.30
390	1.43	1.74	3.01	3.60	3.83	3.83	3.71	2.86	6.42	8.47	2.65	4.00	4.18	4.75	5.00	4.86
391	1.43	1.84	3.27	3.55	4.22	4.22	4.07	2.86	7.43	9.83	2.65	4.50	4.68	5.11	5.50	5.18
392	1.43	1.91	3.50	4.25	4.54	4.54	4.37	2.86	8.11	10.70	3.25	4.95	5.12	5.46	6.00	5.49
393	1.34	1.86	3.55	4.36	4.65	4.65	4.47	2.68	8.30	10.98	3.50	5.25	5.42	5.69	6.50	5.70
394	1.34	1.92	3.74	4.59	4.89	4.89	4.71	2.68	8.63	11.35	3.75	5.65	5.83	6.06	7.00	6.06
395	1.34	2.00	3.37	4.89	5.20	5.20	5.02	2.68	9.11	11.93	4.00	5.10	5.28	5.47	7.50	5.44
396	1.34	2.05	4.04	4.97	5.28	5.28	5.09	2.58	9.35	12.16	4.35	5.65	5.84	5.99	8.00	5.95
397	1.73	2.23	3.58	4.25	4.49	4.49	4.31	3.46	7.72	9.93	4.60	6.50	6.75	7.42	8.00	7.50
398	1.50	1.94	3.23	3.96	4.10	4.10	3.94	3.00	6.93	9.06	3.90	5.60	5.83	6.53	7.00	6.63
400	1.89	2.16	3.05	3.49	3.69	3.69	3.57	3.78	6.66	8.44	3.00	4.35	4.59	5.52	6.00	5.70
401	1.79	2.25	3.47	4.11	4.38	4.38	4.20	3.58	8.23	10.80	3.85	5.40	5.64	6.39	7.00	6.51
402	1.79	2.38	3.90	4.67	4.98	4.98	4.76	3.58	9.15	11.99	4.65	6.55	6.80	7.45	8.00	7.52

APPENDIX C

EXPERIMENTAL DATA AND BACKGROUND INFORMATION ON SILTING

The first part of this appendix briefly describes some relevant physical factors and previous experimental studies in the area of silting and scouring in pipe flow. The remainder of the appendix contains the experimental data and information on scouring generated during this investigation.

The behavior of a moving slurry containing solid particles of greater density than the liquid can be described at various velocities as follows:

1. At very low velocities, the particles will settle out under free or hindered settling.
2. Above a certain "minimum velocity" there will be no particles settling out of the slurry; however, a vertical concentration gradient will exist.
3. When the velocity exceeds the "standard velocity", there will be adequate mixing to eliminate any appreciable vertical concentration gradient.

In a sewage stream, the organic materials and most of the other potentially cohesive materials will be less dense or, at most, of comparable density to water. Therefore, these will be less likely to cause settling problems than the more dense materials such as sand, rocks, bottles, tin cans, etc.--materials which are essentially noncohesive. With noncohesive materials, the movement of solid particles depends only upon the physical properties of the individual particles such as size, shape, and density, and upon their relative position with respect to other particles. Natural sediments are irregular in shape, and, therefore, the definition of size as a single length or diameter must be made arbitrarily. One of the common definitions is the sieve diameter, the size of sieve opening through which the given particle will just pass. In any particular sediment, the sizes of the individual particles may vary over a wide range. However, since larger particles will (with other factors being constant) settle out of a slurry more readily than smaller particles, the design approach taken in the subsequent discussions is to prevent sedimentation of particles of a specific maximum sieve size. Then, any smaller particles will not settle out, but it will be necessary to prevent particles larger than the design size from entering the U-tube.

A single solid particle in a stationary fluid will be acted upon by forces due to buoyancy, gravity, and fluid friction (usually lumped into the "drag" force). A particle released from rest will accelerate until these forces just balance; the resulting velocity is the "terminal velocity". If the upward fluid velocity in a vertical pipe containing a solid particle is equal to the terminal velocity of the particle, then the particle will have no net vertical movement. If the upward fluid velocity exceeds the terminal velocity, the particle will be transported upward. Curve No. 1 in Fig. 15 (contained in the Experimental Results section) shows the terminal velocity of quartz or sand spheres (specific gravity = 2.64) as a function of particle size. Irregular particles will have lower terminal velocities than spheres, of the order of 60 percent of the spherical particle terminal velocity (Ref. 25).

A corresponding curve for the approximate terminal velocity of irregular sand particles is included as curve No. 2 in Fig. 15. This curve could be used as a design basis to ensure that no sand would fail to be carried out of the upward leg of the U-tube.

Ensuring that no restrictive sediment bed will develop on the bottom of the U-tube may require higher velocities than those needed to exceed the settling velocities of the particles. This flow situation is much less tractable, analytically. Several generalizations which have been reported in the literature, all based at least partly on experimental data, are described in the following paragraphs, and results are included in Fig. 15.

Spells (Ref. 26) developed a correlation based upon consideration of the Froude number (to represent gravitational forces) and the Reynolds number (to account for viscous forces) plus experimental data (for particles approximately 50 to 200 microns):

$$\frac{u^2}{g_c\, D_p} = B_1 \left(\frac{D\, u\, \rho_m}{\mu}\right)^{0.775} \left(\frac{\rho_p - \rho}{\rho}\right)$$

where D_p = particle diameter, D = pipe diameter, ρ_p = particle density, ρ_m = mean density of the slurry, and B_1 is an empirical constant which is reported as 0.0251 for the "minimum velocity" and 0.0741 for the "standard velocity". This correlation has given only rough agreement with other published data. Cairns (Ref. 27) considered Spells' equation and used additional data to give his recommended improved form of the equation:

$$\frac{u^2}{g_c\, D_p} = 9.8\, C^{0.3} \left(\frac{D\, u \rho}{\mu}\right)^{0.3} \left(\frac{\rho_p - \rho}{\rho}\right)$$

where C is the solids concentration in volume percent, and the particle size, D_p, is in feet. The results of parametric calculations with each of the above equations are presented in Fig. 15 (curves 3 and 4, respectively).

Curve number 5, shown in Fig. 15, is given by Craven (Ref. 28) and is the one for which the experimental data used to generate it most closely approximate the conditions expected in a typical U-tube application to a sewer line. Therefore, it might be expected to be the most reliable design tool of all the correlations shown in the figure. Craven found that no permanent deposit of sediment would occur in full-flowing pipes if:

$$\frac{Q}{D^2 \, D_p^{1/2} \, g^{1/2} \left(\frac{\rho_p - \rho}{\rho}\right)^{1/2}} > 2.5$$

where Q is the volumetric flowrate through the pipe. The expression on the left side of the equation is dimensionless.

Table C-1 contains the experimental data and other relevant information obtained during the scouring tests of this investigation with the concentric return bend in the bottom of the experimental U-tube.

TABLE C-1

EXPERIMENTAL DATA FOR SCOURING TESTS IN U-TUBE

Run Number/ Material	Differential Head Across U-tube (ft H_2O)	Depth of Scour (inch)	Water Flowrate (gpm)	Observations
429/ 3.5 to 5 mesh glass beads	0.50	3.75	10.2*	No bead movement
	0.75		13.0*	Slight bead shuffling on surface
	1.00		14.8*	Slight "cratering" of surface
	2.25		22.7*	Periodic lifting of beads but no removal
	2.75		24.7*	High surface activity; a few beads removed
	3.50		27.8*	Extreme surface activity; periodic removal of 3-4 beads
	4.75		33.0*	Periodic removal of 5-10 beads; bed surface now lower than before
	5.50	4.50	36.3*	Frequent but irregular removal of 10-15 beads
430/ 3.5 to 5 mesh glass beads	1.00		15.6	No bead action
	1.25			Slight surface activity
	1.50		19.0	Beads jumping into annulus but no removal; "cratering" of surface
	1.75			Increased agitation; no bead removal
	2.00	1.50	21.2*	Removal of beads occurring
	2.25	1.75	22.7	
	2.50	2.25		
	2.75	2.75	24.6*	
	3.00	3.25		
	3.25	3.25	27.0	
	3.75	3.75		Periodic bead removal

* Estimated value

TABLE C-1 (CONT'D)

Run Number/ Material	Differential Head Across U-tube (ft H_2O)	Depth of Scour (inch)	Water Flowrate (gpm)	Observations
430 (Cont'd)	4.25	4.00	31.0*	Periodic bead removal
	4.75	4.25		
	5.25	4.50	35.2*	Test terminated
431/ 8-10 mesh gravel	0.25		8.8	A few grains jumping in annulus
	0.50		10.3	Increased annular activity; slight solids removal
	0.75			Additional solids removal
	1.00	.50		
	1.25	2.75	16.3	Noticeable cratering of solid surface
	1.50	3.00		Solids removal continuing
	1.75	3.00		Solids removal continuing
	2.00	3.50	20.8	Solids removal continuing
	2.25	3.75		Solids removal continuing
	2.50	4.00	23.8	Solids removal continuing
	2.75	4.25		Solids removal continuing
	3.00	4.25	26.3	Solids removal continuing
	3.25	4.50		Solids removal continuing
	3.50	4.75		Solids removal continuing
	3.75	5.00		Solids removal continuing
	4.00	5.50	31.0	Solids removal continuing
	4.25	5.75		Bulb scoured clean; test terminated
432/ 14-18 mesh ground glass	0.25		6.9	Slight solids removal
	0.50	0.25		
	0.75	0.25		
	1.00	3.25	14.2	Considerable scouring

TABLE C-1 (CONT'D)

Run Number/ Material	Differential Head Across U-tube (ft H_2O)	Depth of Scour (inch)	Water Flowrate (gpm)	Observations
432 (Cont'd)	1.25	3.50		
	1.75	4.50	20.4	
	2.25	4.75	23.8	
	2.75	5.25	24.6*	Bulb would probably scour clean given sufficient time
	3.25	5.75	27.8	Bulb scoured clean; test terminated
433/ 30-35 mesh glass beads				Return overloaded with solids, i.e., beads are 7.25 inches up into 2 inch diameter downleg
	0.25	0	3.4	Beads pushed out of downleg; considerable deposition of solids in 90° elbow to upleg; turbulence in annulus but beads not being removed
	0.50		6.4	Additional scouring
	0.75	3.00	10.0	Solids removed from elbow
	1.00	3.50	14.3	
	1.25	4.25	17.0	
	1.50	4.50	18.5	
	1.75	5.00	20.0	
	2.00	5.50	21.5	
	2.25	5.75	22.7	Bulb scoured clean; test terminated

APPENDIX D

SAMPLE OUTPUT FROM U-TUBE DESIGN PROGRAM

Several typical print-outs from the U-tube design program are reproduced in this Appendix. The program was described in the Analytical Studies section. Most of the quantities appearing in the print-outs have been previously defined and/or are listed in the Nomenclature section; however, the following notes may be helpful.

There are a number of physical dimensions given in the print-outs. These are defined in the U-tube schematic diagrams of Fig. 29 and 30; however, some translation is necessary because of the limitations of computer printers: the variable a_0 (shown in Fig. 29) is printed as A9. The quantities "1-PHASE DP" and "2-PHASE DP" are the net pressure differences between the entrance (station 1) and exit (station 12) with water flow only and with air-water flow, respectively. The variable "V. PERM. DP THROAT DP" is the ratio of venturi permanent pressure drop to pressure change from entrance to throat, multiplied by 100 (this is 100 times the variable R, previously defined). The values of XI are values of air-water interfacial area per unit air volume (variable X as previously defined). The nine-column table in the bottom portion of the print-out contains values for each of the printed variables at each of the nine stations listed at the top of the table (the station numbers are those given in Fig. 29 and 30). The pressures given in the lower table of each print-out are static pressures. The air-to-water volume ratios are local values, expressed at the local temperature and pressure.

```
CONTRACTION CONE ANGLE          50.0            SLIP VEL DOWN (FT/SEC)          0.2
EXPANSION CONE ANGLE            15.0            SLIP VEL UP (FT/SEC)            0.2
ELBOW LOSS COEFFICIENT           0.75           XI DOWN (1/FT)                470.
ELBOW CL-TO-FACE/DIA.            1.0            XI UP (1/FT)                  470.

INIT. A/W AT 68F,1ATM(0/0)       5.00           OXYGEN SUPPLIED (MG/L)         14.0
A9  (DOWN-LEG LENGTH)           22.02           KTYPE                           1
A10 (GR. TO EXIST. C-L)          3.50           EXIST. DIA.(INCH)              12.000
A11 (GR. TO CASING BOT.)        30.00           DOWN-LEG DIA.(INCH)            19.000
A15 (UP-LEG LENGTH)             15.28           UP-LEG DIA.(INCH)              13.250
A16 (EXIT HORIZONTAL)            8.00           AMB. PRESS.(FT H20)            34.0
A18 (RISE TO ASPIRATOR C-L)      2.00           TEMPERATURE (F)                82.4
A19 (DROP TO OUTLET C-L)         9.00           QW (GPM)                     1800.
A20 (OVERALL HORIZONTAL)        19.67           SUPE. UW (FT/SEC)               5.11
A21 (ASPIR. STR. EXIT)           1.00           SUPE. THROAT PRESS.(FT H20)    27.10
A22 (ASPIR. STR. ENTR.)          2.00           VENTURI CONTRACTION RATIO       1.00
A23 (ASPIR. LENGTH)              0.30           (P3-P5)/(P3-P4W)*100            0.0

STATION             1         3         5        6         7         8         9        10       12

LOCATION        ENTRANCE  ASP. IN   ASP. OUT  LEG TOP  LEG BOT.  BEND IN  BEND OUT  LEG TOP   EXIT

D.O.(MG/L)        0.20      0.20      0.20     0.32      1.71      1.78      1.81     2.17     2.35

D.N.(MG/L)       13.43     13.43     13.43    13.37     13.73     13.79     13.82    14.01    13.99

P (FT H20)       33.33     27.10     27.10    29.13     43.20     50.75     50.31    35.34    34.03

SAT. D.O.                             6.28     6.51     10.19     10.43     10.36     7.09     6.74

SAT. D.N.                            10.71    11.22     19.60     20.24     20.08    14.07    13.59

A/W (0/0)                             6.52     6.06      3.48      3.37      3.12     4.40     4.77

KL*F4, INCL. ALPHA=0.93 (FPS)         9.09     9.09      9.09      9.09      9.09     9.09     9.09
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```
CONTRACTION CONE ANGLE          50.0            SLIP VEL DOWN (FT/SEC)            0.2
EXPANSION CONE ANGLE            15.0            SLIP VEL UP (FT/SEC)              0.2
ELBOW LOSS COEFFICIENT           0.75           XI DOWN (1/FT)                  470.
ELBOW CL-TO-FACE/DIA.            1.0            XI UP (1/FT)                    470.

INIT. A/W AT 68F,1ATM(O/O)      10.00           OXYGEN SUPPLIED (MG/L)           28.0
A9  (DOWN-LEG LENGTH)           22.02           KTYPE                             1
A10 (GR. TO EXIST. C-L)          3.50           EXIST. DIA.(INCH)                12.000
A11 (GR. TO CASING BOT.)        30.00           DOWN-LEG DIA.(INCH)              19.000
A15 (UP-LEG LENGTH)             15.29           UP-LEG DIA.(INCH)                13.250
A16 (EXIT HORIZONTAL)            9.00           AMB. PRESS.(FT H2O)              34.0
A18 (RISE TO ASPIRATOR C-L)      2.00           TEMPERATURE (F)                  82.4
A19 (DROP TO OUTLET C-L)         8.00           QW (GPM)                       1800.
A20 (OVERALL HORIZONTAL)        19.67           SUPF. UW (FT/SEC)                 5.11
A21 (ASPIR. STR. EXIT)           1.00           SUPF. THROAT PRESS.(FT H2O)      28.86
A22 (ASPIR. STR. ENTR.)          2.00           VENTURI CONTRACTION RATIO         1.00
A23 (ASPIR. LENGTH)              0.30           (P3-P5)/(P3-P4W)*100              0.0


STATION                 1         3         5        6        7        8          9        10       12

LOCATION           ENTRANCE  ASP. IN   ASP. OUT  LEG TOP  LEG BOT.  BEND IN   BEND OUT  LEG TOP   EXIT

D.O.(MG/L)            0.20      0.20      0.20     0.37     2.36     2.45      2.51     3.00     3.23

D.N.(MG/L)           13.43     13.43     13.43    13.37    13.95    14.02     14.07    14.31    14.25

P (FT H2O)           31.08     23.66     23.66    30.63    48.92    50.35     49.88    25.33    34.01

SAT. D.O.                                 6.69     6.87    10.44    10.72     10.61     7.37     7.03

SAT. D.N.                                11.40    11.82    19.35    19.93     19.75    13.94    13.44

A/W (O/O)                                12.22    11.50     7.05     6.84      6.37     8.93     9.67

KL*E4, INCL. ALPHA=0.80 (FPS)             7.22     7.22     7.22     7.22      7.22     7.22     7.22
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```
CONTRACTION CONE ANGLE          50.0          SLIP VEL DOWN (FT/SEC)            0.2
EXPANSION CONE ANGLE            15.0          SLIP VEL UP (FT/SEC)              0.2
ELBOW LOSS COEFFICIENT           0.75         XI DOWN (1/FT)                  470.
ELBOW CL-TO-FACE/DIA.            1.0          XI UP (1/FT)                    470.

INIT. A/W AT 68F,1ATM(O/O)      15.00         OXYGEN SUPPLIED (MG/L)           42.0
A9  (DOWN-LEG LENGTH)           22.02         KTYPE                             1
A10 (GR. TO EXIST. C-L)          3.50         EXIST. DIA.(INCH)                12.000
A11 (GR. TO CASING BOT.)        30.00         DOWN-LEG DIA.(INCH)              19.000
A15 (UP-LEG LENGTH)             15.28         UP-LEG DIA.(INCH)                13.250
A16 (EXIT HORIZONTAL)            9.00         AMB. PRESS.(FT H2O)              34.0
A18 (RISE TO ASPIRATOR C-L)      2.00         TEMPERATURE (F)                  82.4
A19 (DROP TO OUTLET C-L)         8.00         QW (GPM)                       1800.
A20 (OVERALL HORIZONTAL)        19.67         SUPF. UW (FT/SEC)                 5.11
A21 (ASPIR. STR. EXIT)           1.00         SUPF. THROAT PRESS.(FT H2O)      30.51
A22 (ASPIR. STR. ENTR.)          2.00         VENTURI CONTRACTION RATIO         1.00
A23 (ASPIR. LENGTH)              0.30         (P3-P5)/(P3-P4W)*100              0.0


STATION                 1         3         5        6        7        8         9        10       12

LOCATION          ENTRANCE  ASP. IN  ASP. OUT  LEG TOP  LEG BOT.  BEND IN  BEND OUT  LEG TOP    EXIT

D.O.(MG/L)            0.20      0.20      0.20     0.40     2.78     2.89      2.95     3.52     3.77

D.N.(MG/L)           13.43     13.43     13.43    13.38    14.14    14.23     14.28    14.54    14.44

P (FT H2O)           32.73     30.51     30.51    32.06    48.68    50.00     49.51    35.35    34.01

SAT. D.O.                                 7.07     7.21    10.54    10.81     10.69     7.51     7.18

SAT. D.N.                                12.05    12.33    13.19    19.72     19.53    13.89    13.37

A/W (O/O)                                17.31    16.46    10.65    10.36      9.68    13.49    14.59

KL*E4, INCL. ALPHA=0.60 (FPS)             6.31     6.31     6.31     6.31      6.31     6.31     6.31
```

```
CONTRACTION CONE ANGLE           50.0       SLIP VEL DOWN (FT/SEC)          0.2
EXPANSION CONE ANGLE             15.0       SLIP VEL UP (FT/SEC)            0.2
ELBOW LOSS COEFFICIENT            0.75      XI DOWN (1/FT)                470.
ELBOW CL-TO-FACE/DIA.             1.0       XI UP (1/FT)                  470.

INIT. A/W AT 68F,1ATM(0/0)       20.00      OXYGEN SUPPLIED (MG/L)         56.0
A9  (DOWN-LEG LENGTH)            32.02      KTYPE                           1
A10 (GR. TO EXIST. C-L)           2.50      EXIST. DIA.(INCH)              12.000
A11 (GR. TO CASING BOT.)         30.00      DOWN-LEG DIA.(INCH)            19.000
A15 (UP-LEG LENGTH)              15.28      UP-LEG DIA.(INCH)              13.250
A16 (EXIT HORIZONTAL)             8.00      AMB. PRESS.(FT H2O)            34.0
A18 (RISE TO ASPIRATOR C-L)       2.00      TEMPERATURE (F)                82.4
A19 (DROP TO OUTLET C-L)          8.00      QW (GPM)                     1800.
A20 (OVERALL HORIZONTAL)         21.58      SUPE. UW (FT/SEC)               5.11
A21 (ASPIR. STR. EXIT)            1.00      SUPE. THROAT PRESS.(FT H2O)    31.00
A22 (ASPIR. STR. ENTR.)           2.00      VENTURI CONTRACTION RATIO       3.62
A23 (ASPIR. LENGTH)               2.61      (P3-P5)/(P3-P4W)*100           78.6

STATION                      1         3         5         6         7         8         9        10        12

LOCATION              ENTRANCE  ASP. IN  ASP. OUT   LEG TOP   LEG BOT.  BEND IN  BEND OUT  LEG TOP     EXIT

D.O.(MG/L)                0.20      0.20      0.45      0.67      3.23      3.34      3.42      4.02      4.26

D.N.(MG/L)               13.43     13.43     13.40     13.37     14.29     14.39     14.44     14.70     14.58

P (FT H2O)               39.14     35.32     32.05     33.40     48.48     49.69     49.16     35.37     34.01

SAT. D.O.                                     7.43      7.50     10.57     10.82     10.70      7.59      7.26

SAT. D.N.                                    12.66     12.92     19.07     19.56     19.35     13.86     13.33

A/W (0/0)                                    21.51     21.01     14.27     13.91     13.04     18.06     19.53

KL*E4, INCL. ALPHA=0.80 (FPS)                 5.74      5.74      5.74      5.74      5.74      5.74      5.74
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CONTRACTION CONE ANGLE            50.0          SLIP VEL DOWN (FT/SEC)          0.2
EXPANSION CONE ANGLE              15.0          SLIP VEL UP (FT/SEC)            0.2
ELBOW LOSS COEFFICIENT             0.75         XI DOWN (1/FT)                470.
ELBOW CL-TO-FACE/DIA.              1.0          XI UP (1/FT)                  470.

INIT. A/W AT ABS,1ATM(O/O)        15.00         OXYGEN SUPPLIED (MG/L)         42.0
A9  (DOWN-LEG LENGTH)             32.02         KTYPE                           1
A10 (GR. TO EXIST. C-L)            3.50         EXIST. DIA.(INCH)              12.000
A11 (GR. TO CASING BOT.)          40.00         DOWN-LEG DIA.(INCH)            19.000
A15 (UP-LEG LENGTH)               25.28         UP-LEG DIA.(INCH)              13.250
A16 (EXIT HORIZONTAL)              3.00         AMB. PRESS.(FT H2O)            34.0
A18 (RISE TO ASPIRATOR C-L)        2.00         TEMPERATURE (F)                82.4
A19 (DROP TO OUTLET C-L)           9.00         QW (GPM)                     1800.
A20 (OVERALL HORIZONTAL)          21.30         SUPF. UW (FT/SEC)               5.11
A21 (ASPIR. STR. EXIT)             1.00         SUPF. THROAT PRESS.(FT H2O)    31.00
A22 (ASPIR. STR. ENTR.)            2.00         VENTURI CONTRACTION RATIO       2.26
A23 (ASPIR. LENGTH)                1.93         (P3-P5)/(P3-P4W)*100           68.0

STATION               1          3          5          6          7          8          9         10         12

LOCATION          ENTRANCE   ASP. IN    ASP. OUT   LEG TOP    LEG BOT.   BEND IN    BEND OUT   LEG TOP     EXIT

D.O.(MG/L)          0.20       0.20       0.26       0.44       3.53       3.63       3.68       4.46       4.62

D.N.(MG/L)         13.43      13.43      13.42      13.39      15.03      15.14      15.20      15.66      15.50

P (FT H2O)         34.60      32.62      31.54      33.11      58.07      59.44      58.96      35.35      34.02

SAT. D.O.                                 7.21       7.45      12.46      12.74      12.63       7.40       7.09

SAT. D.N.                                12.46      12.80      23.01      23.57      23.38      13.94      13.41

A/W (O/O)                                16.74      15.93       8.35       8.63       8.05      13.32      14.42

KL*E4, INCL. ALPHA=0.90 (E25)             5.69       5.69       5.69       5.69       5.69       5.69       5.69
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CONTRACTION CONE ANGLE            50.0          SLIP VEL DOWN (FT/SEC)          0.2
EXPANSION CONE ANGLE              15.0          SLIP VEL UP (FT/SEC)            0.2
ELBOW LOSS COEFFICIENT             0.75         XI DOWN (1/FT)                470.
ELBOW CL-TO-FACE/DIA.              1.0          XI UP (1/FT)                  470.

INIT. A/W AT ABS.1ATM(O/O)        15.00         OXYGEN SUPPLIED (MG/L)         42.0
A9  (DOWN-LEG LENGTH)             42.02         KTYPE                           1
A10 (CP. TO EXIST. C-L)            3.50         EXIST. DIA.(INCH)              12.000
A11 (CP. TO CASING BOT.)          50.00         DOWN-LEG DIA.(INCH)            19.000
A15 (UP-LEG LENGTH)               35.28         UP-LEG DIA.(INCH)              13.250
A16 (EXIT HORIZONTAL)              8.00         AMB. PRESS.(FT H2O)            34.0
A18 (RISE TO ASPIRATOR C-L)        2.00         TEMPERATURE (F)                82.4
A19 (DROP TO OUTLET C-L)           8.00         QW (GPM)                     1800.
A20 (OVERALL HORIZONTAL)          21.52         SUPE. UW (FT/SEC)               5.11
A21 (ASPIR. STR. EXIT)             1.00         SUPE. THROAT PRESS.(FT H2O)    31.00
A22 (ASPIR. STR. ENTR.)            2.00         VENTURI CONTRACTION RATIO       3.44
A23 (ASPIR. LENGTH)                2.55         (P3-P5)/(P3-P4W)*100           68.9

STATION             1          3          5         6         7         8         9        10        12

LOCATION        ENTRANCE   ASP. IN    ASP. OUT  LEG TOP   LEG BOT.  BEND IN  BEND OUT  LEG TOP    EXIT

D.O.(MG/L)        0.20       0.21       0.37      0.54      4.22      4.30      4.36      5.27      5.36

D.N.(MG/L)       13.43      13.43      13.41     13.39     15.91     16.10     16.17     16.81     16.59

P (FT H2O)       37.47      35.46      32.33     33.99     67.55     68.96     68.49     35.33     34.00

SAT. D.O.                              7.51      7.64     14.33     14.57     14.56      7.32      7.01

SAT. D.N.                             12.60     13.15     26.87     27.45     27.27     13.96     13.44

A/W (O/O)                             16.29     15.51      7.53      7.17      6.86     13.17     14.27

KL*E4, INCL. ALPHA=0.80 (SEC)          5.22      5.22      5.22      5.22      5.22      5.22      5.22
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CONTRACTION CONE ANGLE           53.0              SLIP VEL DOWN (FT/SEC)           0.2
EXPANSION CONE ANGLE             15.0              SLIP VEL UP (FT/SEC)             0.2
ELBOW LOSS COEFFICIENT            0.75             KI DOWN (1/FT)                 470.
ELBOW CL-TO-FACE/DIA.             1.0              KI UP (1/FT)                   470.

INIT. A/W AT ASP.STAT(O/O))      13.00             OXYGEN SUPPLIED (MG/L)          42.0
A9  (DOWN-LEG LENGTH)            52.02             KTYPE                            1
A10 (GR. TO EXIST. C-L)           3.50             EXIST. DIA.(INCH)               12.000
A11 (GR. TO CASING BOT.)         40.00             DOWN-LEG DIA.(INCH)             19.000
A15 (UP-LEG LENGTH)              45.28             UP-LEG DIA.(INCH)               13.250
A16 (EXIT HORIZONTAL)             4.00             AMB. PRESS.(FT H2O)             34.0
A18 (RISE TO ASPIRATOR C-L)       2.00             TEMPERATURE (F)                 82.4
A19 (DROP TO OUTLET C-L)          4.00             QW (GPM)                      1800.
A20 (OVERALL HORIZONTAL)         22.22             SUPE. U4 (FT/SEC)                5.11
A21 (ASPIR. STR. EXIT)            1.00             SUPE. THROAT PRESS.(FT H2O)     31.00
A22 (ASPIR. STR. ENTR.)           2.00             VENTURI CONTRACTION RATIO        4.42
A23 (ASPIR. LENGTH)               2.95             (P3-P5)/(P3-P4W)*100            71.3

STATION                 1          3          5         6         7          8          9         10         12

LOCATION            ENTRANCE   ASP. IN    ASP. OUT   LEG TOP   LEG BOT.   BEND IN    BEND OUT   LEG TOP     EXIT

D.O.(MG/L)            0.20       0.31       0.50      0.65      4.85       4.93       4.98      6.00       6.05

D.N.(MG/L)           13.43      13.43      13.41     13.40     16.96      17.08      17.15     17.96      17.69

P (FT H2O)           40.77      33.51      32.15     34.76     77.14      79.59      78.13     35.34      34.00

SAT. D.O.                                  7.69      7.80     16.31      16.60      16.49      7.24       6.94

SAT. D.N.                                 13.10     13.46     30.73      31.30      31.20     14.00      13.47

A/W (O/O)                                 15.90     15.15      6.54       6.41       5.95     13.01      14.11

KL*F4, INCL. ALPHA=0.63 (FPS)              4.85      4.85      4.95       4.85       4.85      4.85       4.95
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CONTRACTION CONE ANGLE        50.0           SLIP VEL DOWN (FT/SEC)            0.2
EXPANSION CONE ANGLE          15.0           SLIP VEL UP (FT/SEC)              0.2
ELBOW LOSS COEFFICIENT         0.75          XI DOWN (1/FT)                  470.
ELBOW CL-TO-FACE/DIA.          1.0           XI UP (1/FT)                    470.

INIT. A/W AT ARE,1ATM(O/O)    20.00          OXYGEN SUPPLIED (MG/L)           56.0
A9  (DOWN-LEG LENGTH)         32.02          KTYPE                             1
A10 (GR. TO EXIST. C-L)        3.50          EXIST. DIA.(INCH)                12.000
A11 (GR. TO CASING BOT.)      40.00          DOWN-LEG DIA.(INCH)              19.000
A15 (UP-LEG LENGTH)           25.28          UP-LEG DIA.(INCH)                13.250
A16 (EXIT HORIZONTAL)          8.00          AMB. PRESS.(FT.H2O)              34.0
A18 (RISE TO ASPIRATOR C-L)    2.00          TEMPERATURE (F)                  92.4
A19 (DROP TO OUTLET C-L)       8.00          QW (GPM)                       1800.
A20 (OVERALL HORIZONTAL)      21.94          SUPE. UW (FT/SEC)                 5.11
A21 (ASPIR. STR. EXIT)         1.00          SUPE. THROAT PRESS.(FT H2O)      32.27
A22 (ASPIR. STR. ENTR.)        2.00          VENTURI CONTRACTION RATIO         3.52
A23 (ASPIR. LENGTH)            2.57          (P3-P5)/(P3-P4W)*100             77.1

STATION             1         4         5        6        7         8         9        10        12

LOCATION        ENTRANCE  ASP. IN   ASP. OUT  LEG TOP  LEG BOT.  BEND IN  BEND OUT  LEG TOP     EXIT

D.O.(MG/L)        0.20      0.20      0.44     0.65     4.07      4.17      4.24     5.06      5.20

D.N.(MG/L)       13.43     13.43     13.42    13.41    15.34     15.45     15.52    15.97     15.76

P (FT H2O)       33.10     36.83     33.32    34.71    57.63     58.91     58.40    35.36     34.00

SAT. D.O.                             7.72     7.80    12.49     12.75     12.63     7.50      7.18

SAT. D.N.                            13.16    13.44    22.79     23.30     23.10    13.90     13.36

A/W (O/O)                            21.07    20.22    11.91     11.64     10.88    17.97     19.34

KL*F4, INCL. ALPHA=0.90 (FPS)         5.25     5.25     5.25      5.25      5.25     5.25      5.25
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CONTRACTION CONE ANGLE          50.0           SLIP VEL DOWN (FT/SEC)            0.2
EXPANSION CONE ANGLE            15.0           SLIP VEL UP (FT/SEC)              0.2
ELBOW LOSS COEFFICIENT           0.75          XI DOWN (1/FT)                  470.
ELBOW CL-TO-FACE/DIA.            1.0           XI UP (1/FT)                    470.

INIT. A/W AT 68F,1ATM(0/0)      15.00          OXYGEN SUPPLIED (MG/L)           42.0
A9  (DOWN-LEG LENGTH)           24.73          KTYPE                             1
A10 (GR. TO EXIST. C-L)          4.60          EXIST. DIA.(INCH)                10.000
A11 (GR. TO CASING BOT.)        30.00          DOWN-LEG DIA.(INCH)              12.000
A15 (UP-LEG LENGTH)             18.23          UP-LEG DIA.(INCH)                 7.981
A16 (EXIT HORIZONTAL)            8.00          AMB. PRESS.(FT H2O)              34.0
A18 (RISE TO ASPIRATOR C-L)      3.00          TEMPERATURE (F)                  82.4
A19 (DROP TO OUTLET C-L)         5.00          QW (GPM)                        670.
A20 (OVERALL HORIZONTAL)        20.92          SUPF. UW (FT/SEC)                 2.74
A21 (ASPIR. STR. EXIT)           0.93          SUPF. THROAT PRESS.(FT H2O)      31.00
A22 (ASPIR. STR. ENTR.)          1.67          VENTURI CONTRACTION RATIO         7.44
A23 (ASPIR. LENGTH)              2.82          (P3-P5)/(P3-P4W)*100             66.8

STATION             1          3          5        6         7        8          9         10       12

LOCATION        ENTRANCE   ASP. IN   ASP. OUT  LEG TOP   LEG BOT.  BEND IN   BEND OUT  LEG TOP    EXIT

D.O.(MG/L)         0.20      0.20      0.55      1.08      3.72      3.72      3.79      4.36      4.53

D.N.(MG/L)        13.43     13.43     13.37     13.37     14.67     14.67     14.74     15.03     14.91

P (FT H2O)        40.40     37.33     33.10     35.85     52.57     52.57     52.05     35.04     34.01

SAT. D.O.                             7.47      7.49     11.20     11.20     11.08      7.33      7.08

SAT. D.N.                            13.09     13.07     20.83     20.83     20.62     13.81     13.41

A/W (0/0)                            16.39     16.09     10.09     10.09      9.15     13.53     14.50

KL*E4, INCL. ALPHA=0.80 (FPS)         6.32      6.32      6.32      6.32      6.32      6.32      6.32
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CONTRACTION CONE ANGLE              50.0          SLIP VEL DOWN (FT/SEC)             0.2
EXPANSION CONE ANGLE                15.0          SLIP VEL UP (FT/SEC)               0.2
ELBOW LOSS COEFFICIENT               0.75         XI DOWN (1/FT)                   470.
ELBOW CL-TO-FACE/DIA.                1.0          XI UP (1/FT)                     470.

INIT. A/W AT 68F,1ATM(O/O)          10.00         OXYGEN SUPPLIED (MG/L)            28.0
A9  (DOWN-LEG LENGTH)               23.75         KTYPE                              1
A10 (GR. TO EXIST. C-L)              8.67         EXIST. DIA.(INCH)                  7.981
A11 (GR. TO CASING BOT.)            30.00         DOWN-LEG DIA.(INCH)               15.250
A15 (UP-LEG LENGTH)                 18.75         UP-LEG DIA.(INCH)                 10.020
A16 (EXIT HORIZONTAL)                8.00         AMB. PRESS.(FT H2O)               34.0
A18 (RISE TO ASPIRATOR C-L)          7.00         TEMPERATURE (F)                   82.4
A19 (DROP TO OUTLET C-L)             0.0          QW (GPM)                        1000.
A20 (OVERALL HORIZONTAL)            22.74         SUPF. UW (FT/SEC)                  6.41
A21 (ASPIR. STR. EXIT)               0.67         SUPF. THROAT PRESS.(FT H2O)       31.00
A22 (ASPIR. STR. ENTR.)              1.33         VENTURI CONTRACTION RATIO          2.03
A23 (ASPIR. LENGTH)                  1.17         (P3-P5)/(P3-P4W)*100              64.3


STATION                    1          3          5         6         7         8         9        10        12
LOCATION               ENTRANCE   ASP. IN   ASP. OUT   LEG TOP  LEG BOT.   BEND IN  BEND OUT   LEG TOP     EXIT
D.O.(MG/L)               0.20       0.20       0.24      0.33      2.78      2.84      2.88      3.45      3.65
D.N.(MG/L)              13.43      13.43      13.43     13.41     14.43     14.49     14.52     14.82     14.73
P (FT H2O)              40.43      33.03      31.71     32.53     52.53     53.47     53.03     35.11     34.02
SAT. D.O.                                      7.35      7.32     11.09     11.29     11.17      7.23      6.95
SAT. D.N.                                     12.53     12.56     20.36     21.24     21.07     13.89     13.48
A/W (O/O)                                     11.03     10.75      6.46      6.34      5.94      9.89      9.58
KL*E4, INCL. ALPHA=0.90 (FPS)                  7.24      7.24      7.24      7.24      7.24      7.24      7.24
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KTYPE                                   1          A11 (GR. TO CASING BOT.)          30.50
INIT. A/W AT 68F,1ATM (O/O)         22.00          A25 (STR. DROP TO DIFFUSER)       -0.00
OXYGEN SUPPLIED (MG/L)              55.0           EXIST. PIPE I.D.(INCH)            23.250
WATER FLOWRATE (GPM)               3470.           DOWN PIPE I.D.(INCH)              23.250
VENTURI CONTRACTION RATIO            7.72          UP PIPE I.D.(INCH)                26.500

AMBIENT PRESS.(FT H2O)              33.6           TEMPERATURE (F)                   75.0
A9 (DOWN-LEG LENGTH, FT)            24.65          SUPERFICIAL UW IN (FT/SEC)         2.62
A10 (GRADE TO EXIST. C-L)            0.0           SUPERFICIAL UW UP (FT/SEC)         2.02
A15 (UP-LEG LENGTH)                 16.15          SUPF. THROAT PRESS.(FT H2O)       29.19
A16 (EXIT HORIZONTAL)                0.0           V. PERM. DP/THROAT DP (O/O)       77.4
A18 (RISE TO ASPIRATOR C-L)          0.0           ELBOW LOSS COEFFICIENT             0.75
A19 (DROP TO OUTLET C-L)            12.50          ELBOW CL-TO-FACE/DIA.              1.0
A20 (OVERALL HORIZONTAL)            13.60          SLIP VELOCITY DOWN (FT/SEC)        0.2
A21 (SPOOL AT ASP. EXIT)             0.0           SLIP VELOCITY UP (FT/SEC)          0.2
A22 (SPOOL AT ASP. ENTR.)            0.0           XI DOWN (1/FT)                   470.
1-PHASE DP (FT H2O)                 -3.18          XI UP (1/FT)                     470.
2-PHASE DP (FT H2O)                  1.86

STATION               1          3         5        6         7         8          9        10        12

LOCATION       ENTRANCE   ASP. IN   2-PHASE  LEG TOP  LEG BOT.  BEND IN   BEND OUT   LEG TOP      EXIT

D.O.(MG/L)         1.00      1.00      1.44     1.61      4.01      4.01      4.34      5.52      5.52

D.N.(MG/L)        14.04     14.04     13.95    13.91     14.86     14.86     15.15     15.61     15.61

P (FT H2O)        35.46     35.46     30.61    32.10     48.59     48.55     48.46     33.60     33.60

SAT. D.O.                              7.60     7.70     11.36     11.36     11.28      7.65      7.65

SAT. D.N.                             12.79    13.13     20.21     20.21     20.18     13.94     13.94

A/W (O/O)                             23.69    22.57     14.72     14.72     12.69     18.16     18.16

KL*E4, INCL. ALPHA=0.92 (FPS)          6.33     6.33      6.33      6.33      6.33      6.33      6.33
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KTYPE                               2              A11 (GR. TO CASING BOT.)            30.00
INIT. A/W AT 68F,1ATM (O/O)     15.00              A25 (STR. DROP TO DIFFUSER)          0.0
OXYGEN SUPPLIED (MG/L)          42.0               EXIST. PIPE I.D.(INCH)               7.981
WATER FLOWRATE (GPM)           300.                DOWN PIPE I.D.(INCH)                 7.981
VENTURI CONTRACTION RATIO        1.00              UP PIPE I.D.(INCH)                   5.047

AMBIENT PRESS.(FT H2O)          34.0               TEMPERATURE (F)                     82.4
A9 (DOWN-LEG LENGTH, FT)        23.97              SUPERFICIAL UW IN (FT/SEC)           1.92
A10 (GRADE TO EXIST. C-L)        4.34              SUPERFICIAL UW UP (FT/SEC)           4.81
A15 (UP-LEG LENGTH)             24.12              SUPE. THROAT PRESS.(FT H2O)          0.01
A16 (EXIT HORIZONTAL)            8.00              V. PERM. DP/THROAT DP (O/O)          0.0
A18 (RISE TO ASPIRATOR C-L)      0.0               ELBOW LOSS COEFFICIENT               0.75
A19 (DROP TO OUTLET C-L)         0.0               ELBOW CL-TO-FACE/DIA.                1.0
A20 (OVERALL HORIZONTAL)         9.92              SLIP VELOCITY DOWN (FT/SEC)          0.2
A21 (SPOOL AT ASP. EXIT)         0.0               SLIP VELOCITY UP (FT/SEC)            0.2
A22 (SPOOL AT ASP. ENTR.)        0.0               XI DOWN (1/FT)                     470.
1-PHASE DP (FT H2O)              1.45              XI UP (1/FT)                       470.
2-PHASE DP (FT H2O)              5.15

STATION             1          3          5         6         7         8          9         10        12

LOCATION        ENTRANCE.  ASP. IN    2-PHASE   LEG TOP   LEG BOT.  BEND IN   BEND OUT   LEG TOP     EXIT

D.O.(MG/L)        0.20       0.20       0.20      0.20      3.34      3.34       3.41      4.19      4.36

D.N.(MG/L)       13.43      13.43      -0.00     13.43     15.43     15.43      15.50     15.85     15.69

P (FT H2O)       39.16      39.16      39.78      0.00     58.53     58.53      57.88     34.90     34.01

SAT. D.O.                               9.22      9.22     12.64     12.64      12.49      7.36      7.13

SAT. D.N.                              15.72     15.72     23.15     23.15      22.90     13.73     13.39

A/W (O/O)                              14.09     14.09      9.33      9.33       8.26     13.69     14.46

KL*F4, INCL. ALPHA=0.80 (FPS)           6.52      6.52      6.52      6.52       6.52      6.52      6.52
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